Tacoma Narrows Tidal Power Feasibility Study

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Publication date:
2007

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Document Version
Publisher's PDF, also known as Version of record

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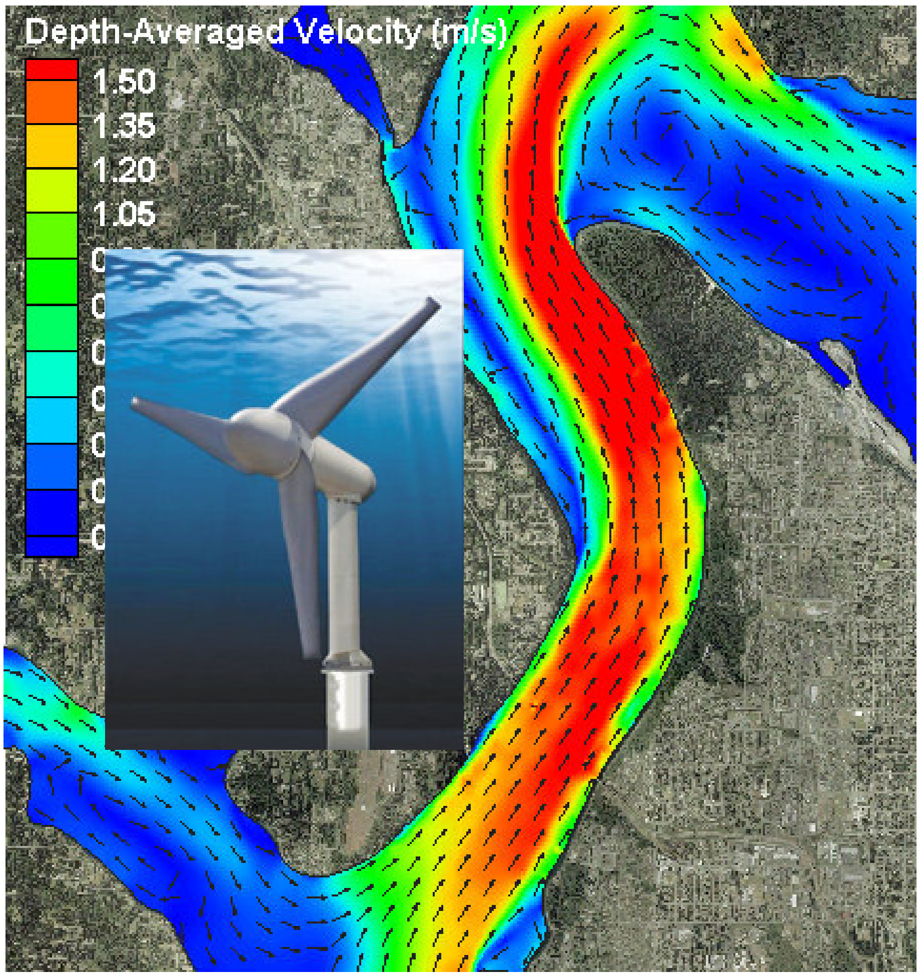
Final Report



December 31, 2007

Puget Sound Tidal Power LLC

For Tacoma Power, Tacoma Public Utilities, City of Tacoma, Washington

Prepared in response to Tacoma Power RFP PG06-0810F

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Acknowledgements

This study was a team effort from an outstanding group of experts. Particular thanks are due to Dr. Vladimir Shepsis, Dr. Bruce Adee, Drs. Ariel Bergmann and Julie Gustanski, Pam Klatt, and Williamson Associates Inc., who contributed significantly beyond their scopes of work and whose flexibility and collaboration made this project more successful. Scott Amsden of Tacoma Power directed the project with adaptability and responsiveness.

Disclaimers

The information and conclusions in this report are based on the best available information at the time of the study. Several topics of the study, including environmental and energy project permitting and tidal turbine technology development, are in a state of flux and/or rapid development. Conclusions regarding these topics should be considered current only at the time of the report. Conclusions regarding specific tidal turbine technology developers are based on the information they provided or could be obtained from public sources. Many developers did not reply to the study survey, for a variety of reasons. The description of turbine technologies and companies is intended to be general, and persons interested in specific technologies should contact the developers directly.

There are some errors in the figure numbering in the appendices because of software problems when documents with different heading and figure caption settings were combined. The minor errors should not impair understanding the documents. All contributed documents are provided in their original form on the CD version of this report.

The lead author, Burton Hamner, takes full responsibility for any inaccuracies in the report.

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Executive Summary

The Tacoma Narrows Tidal Power Feasibility Study was conducted to determine if Tacoma Power could generate commercial-scale, cost-competitive renewable power from the energy of marine tidal currents in the Tacoma Narrows of Puget Sound, Washington.

Tacoma Power envisions a four-phase investigation. In Phase I, completed in 2005-2006, the Electric Power Research Institute (EPRI) did a "bench" study and concluded that an array of 64 large double-rotor tidal turbines could generate about 16MW of power at a site in Tacoma Narrows. EPRI concluded that the Cost of Energy would be competitive but it was not able to include costs for environmental permitting and regulation and studies.

In Phase II, this Study, a team of leading Northwest oceanographers, marine technology experts and firms, environmental and regulatory experts and economists used new field data and advanced modeling to determine the actual power available. The tidal turbine technology available was surveyed and evaluated for its application to the site. Studies and permits were estimated and economics considered.

Phase III would be a pilot project to demonstrate a few tidal turbines in the Narrows, following approval by authorities. Phase IV would be the commercial array.

The main Phase II Feasibility Study conclusions are:

Commercial-scale tidal power generation in Tacoma Narrows does not appear feasible for at least another eight to ten years. The amount of power that could be generated is small compared to Tacoma Power's needs. Under existing economic conditions commercial-scale tidal power generation is not economically competitive compared to other resources such as wind power.

However, over eight or ten years, conditions will change and Tacoma Power may want to develop the resource. To preserve its permit and license options for the site, Tacoma Power should renew its preliminary permit in 2009 and apply for a five year pilot project license and project that would be funded by third parties. By the time a pilot project is completed there may be advances in tidal turbine technology that increase power and decrease costs and impacts to the point that the project is economically desirable and environmentally feasible.

More specific conclusions of this Feasibility Study are:

The EPRI report is in general correct about the amount of energy available from the tidal currents, given the assumptions used, and the EPRI report overall does an adequate job to characterize the entire site and the basics of tidal power generation.

The amount of power that could be generated at the site using any existing tidal turbine, even in advanced form five years from now, is less than EPRI estimated. The turbines are designed to make rated power at velocities of 2 m/s or more. Such velocities happen at the best site in the Narrows not more than 20% of the time. It is almost certain than no turbine, even one 16m or 50 ft in diameter (the height of a 5-floor building) would make more than 100 kW/hr. Thus it would take at least 100 turbines to make 10 MW/hr on average. In comparison, Tacoma in 2005 needed 685 MW/hr on average to serve its customers.

In the array located for maximum power generation, the turbines are located along 13 transects and spaced relatively close together. This creates a "forest" of turbines in the Point Evans area. It would be impossible for any large drifting object such as a log or a whale to pass through this array without encountering several turbines. Reducing array density to reduce impact potential sharply reduces power output.

There are no tidal turbines that could be effectively tested at full scale in Tacoma Narrows for at least five years. The leading developers are only now getting their large units installed for long-term tests. It will be several years before their reliability can be established. Then a pilot project must be designed and permits obtained.

A variety of environmental studies are likely to be required. Studies and permits needed for a commercial turbine array could cost approximately $6 million and take over five years from start to complete, not including ongoing monitoring of the array.

Although these are significant impediments to a commercial-scale project, there is good news for Tacoma Power. New federal funding has been authorized that will pay for extensive research and development of tidal power in the USA. Tacoma Power is the best-positioned utility in the country to develop tidal power resources and is very likely to obtain funding for pilot project development and permitting if it is requested.

The benefits of continuing with a pilot project include:

- protection of rights to a demonstrable renewable energy resource in Tacoma's "front yard",
- attraction of technology developers and new jobs to Tacoma,
- development of hydrokinetic technology that could benefit Tacoma Power in its existing hydroelectric power supply system,
- obtain grant funding for more comprehensive examination of all Tacoma Power's potential renewable energy resources

The most promising pilot project design is a floating barge installation that will allow testing of different turbines at low relative cost and enable rapid removal if negative impacts are observed. This would be a nationally-recognized and funded tidal turbine testing facility.

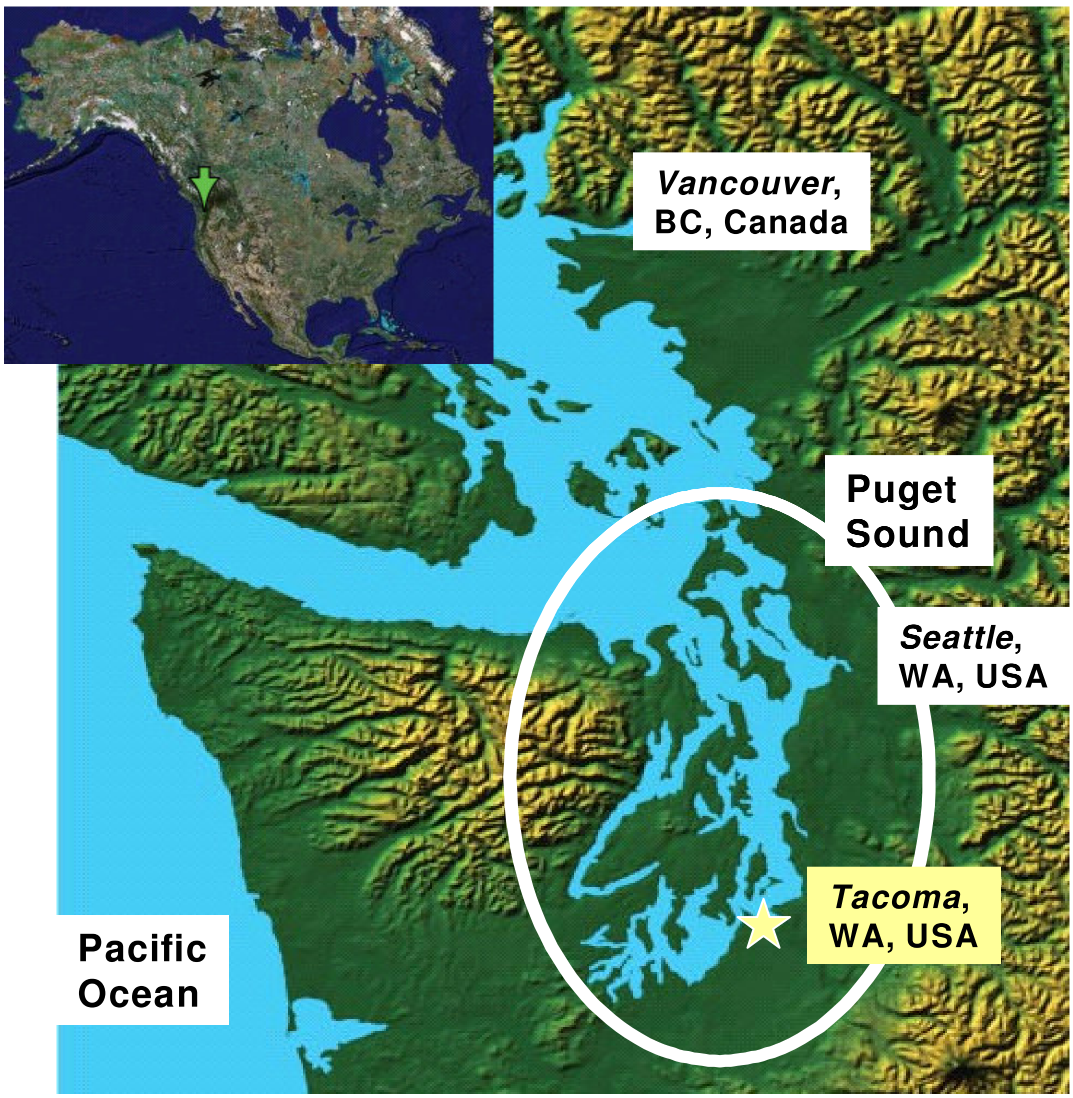
Because the probability that Tacoma Power could obtain external grant funding to pay for most of it, we recommend that Tacoma Power proceed with an application for a second FERC preliminary permit and then a five-year Pilot Project License. A pilot project description and budget should be prepared soon and circulated to potential funding authorities so appropriations can be made in 2008.

1 Introduction

1.1 Tacoma Power and Renewable Energy

The City of Tacoma, Washington is located in the northwest corner of the continental USA, near the border with Canada. It extends along the southeast shores of Puget Sound, Washington's large coastal estuary (Figure 1). The City has about 200,000 people.

Figure 1: Regional Map of Tacoma, Washington, USA

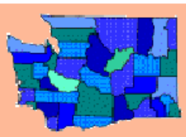


Tacoma Power is the public electric utility agency for the City. In 2005 it provided electricity to 159,182 customers over 180 square miles. It had 713 MW of hydroelectric generation capacity that met about 42% of its customers' requirements. The additional electricity needed is purchased from other sources. 89% of all Tacoma Power's source is from hydroelectric dams. The 2005 electric power delivered was about 6 million MWhr/yr, about 685 MW/hr, at an average cost of 6.6 cents per kWhr, among the lowest rates in the USA.

Like most other utilities in Washington, Tacoma Power is covered by Initiative 937, passed in 2006. The new law requires that utilities provide 15% of their power from renewable sources by 2020. The law specifically excludes hydropower from existing or new dams. Since Tacoma Power already gets 89% of its power from hydroelectric sources, other acquisitions required by the initiative will likely exceed Tacoma Power's supply needs and require the utility to acquire resources prior to need. The new portfolio goal of 15% renewable energy means that Tacoma Power would require about 900,000 MW/yr of renewable energy based on its 2005 distribution of 6 million MW/yr. It would take approximately three of the largest recent wind energy projects in the world to make 900,000 MW output. Tacoma Power must consider all possible sources and focus on, indeed compete for, large project sources to meet its requirements for renewable energy.

It is helpful to compare alternative energy sources against the most common type: wind power. Wind turbines are proven, in production, and increasing in number quickly around the world. Figure 2 ,below summarizes commercial-scale wind power development in Washington State.

Figure 2: Wind Power Development in Washington



State Summary:

Installed MW = 818*
Under Construction= 140 MW

Wind Energy Potential:
Average Power Output (MW): 3,740
Annual kWh: 33 Billion
Rank in US: 24th**

Updated: June 30, 2007

Washington State

Wind Energy Development

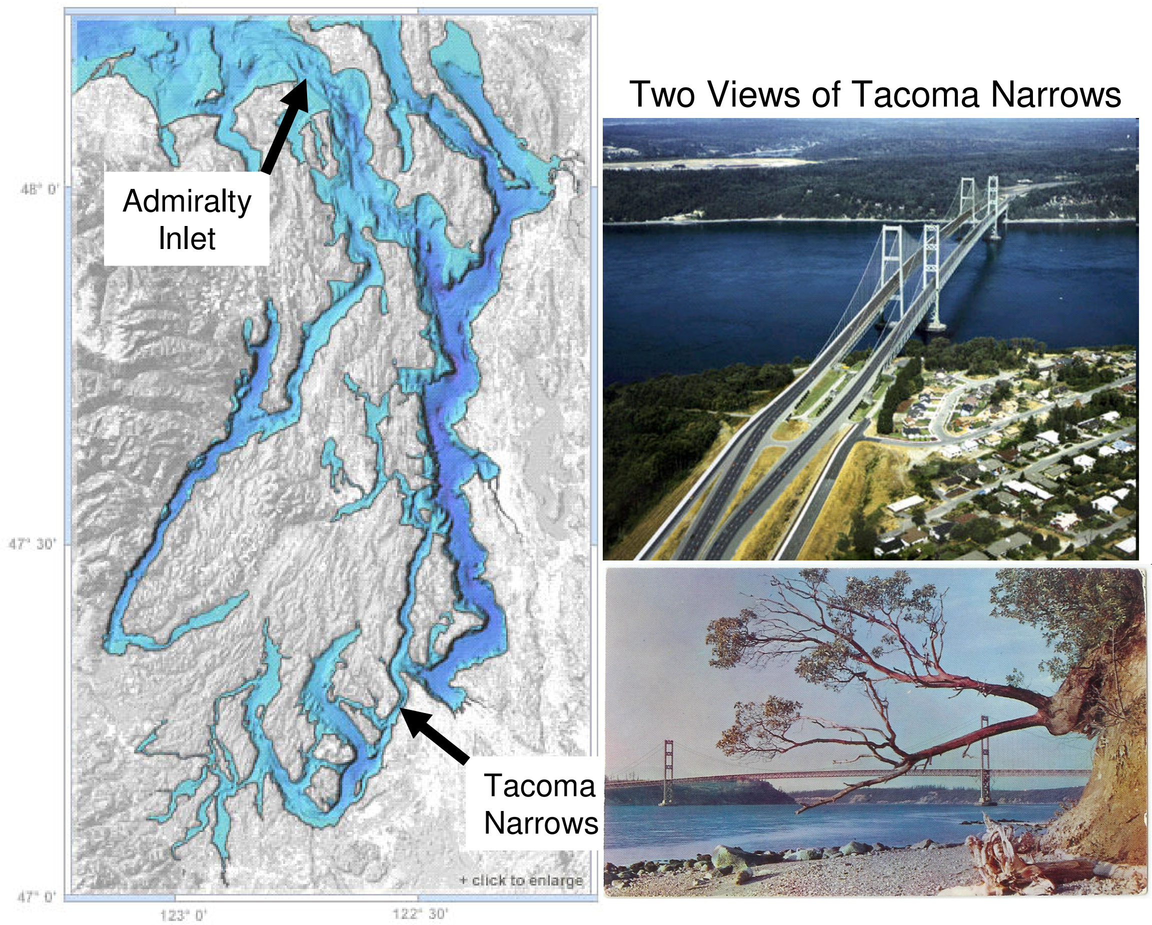
Existing Project or Area	Owner	Date Online	MW	Power Purchaser/ User	Turbines/ (Units)
Stateline Wind Project, Phase I (Walla Walla)	FPL Energy	Dec 2001	176.9	PPM Energy	Vestas V-47 (268)
Nine Canyon Wind Farm	Energy Northwest	Sep 2002	48.0	Public Power Members of Energy Northwest	Bonus 1300 (37)
Nine Canyon Phase II	Energy Northwest	4th Q 2003	15.6	Energy Northwest	Bonus 1300 (12)
Hopkins Ridge Wind Farm	Puget Sound Energy	2005	149.4	Puget Sound Energy	Vestas 1.8 MW (83)
Big Horn Wind Power Project	PPM Energy	2006	199.5	Modesto-Santa Clara-Redding Public Power Agency	GE Energy 1.5-MW (133)
Wild Horse Wind Power Project	Puget Sound Energy	2006	228.6	Puget Sound Energy	Vestas 1.8-MW (127)

In general the projects are over 100MW capacity. A summary of 46 wind projects, existing and proposed, in both Washington and Texas (the latter having the largest number of projects of any state) shows an average project size of 117MW capacity. These figures are important to consider when evaluating the power potential of other sources such as tidal energy, which must compete for available capital for energy development.

1.2 Tacoma Narrows Tidal Channel

The City of Tacoma sits in part along the shore of the Tacoma Narrows in the Puget Sound of Washington, a major coastal estuary. The entrance to Puget Sound is at Admiralty Inlet to the north (Figure 3). The Tacoma Narrows is a constriction, about 7 miles long and one mile wide, and 150-200 feet deep, that separates northern and southern Puget Sound. The Narrows is famous for its strong tidal currents which can reach 6 knots or 3 meters/sec (m/s).

Figure 3: Puget Sound and Tacoma Narrows

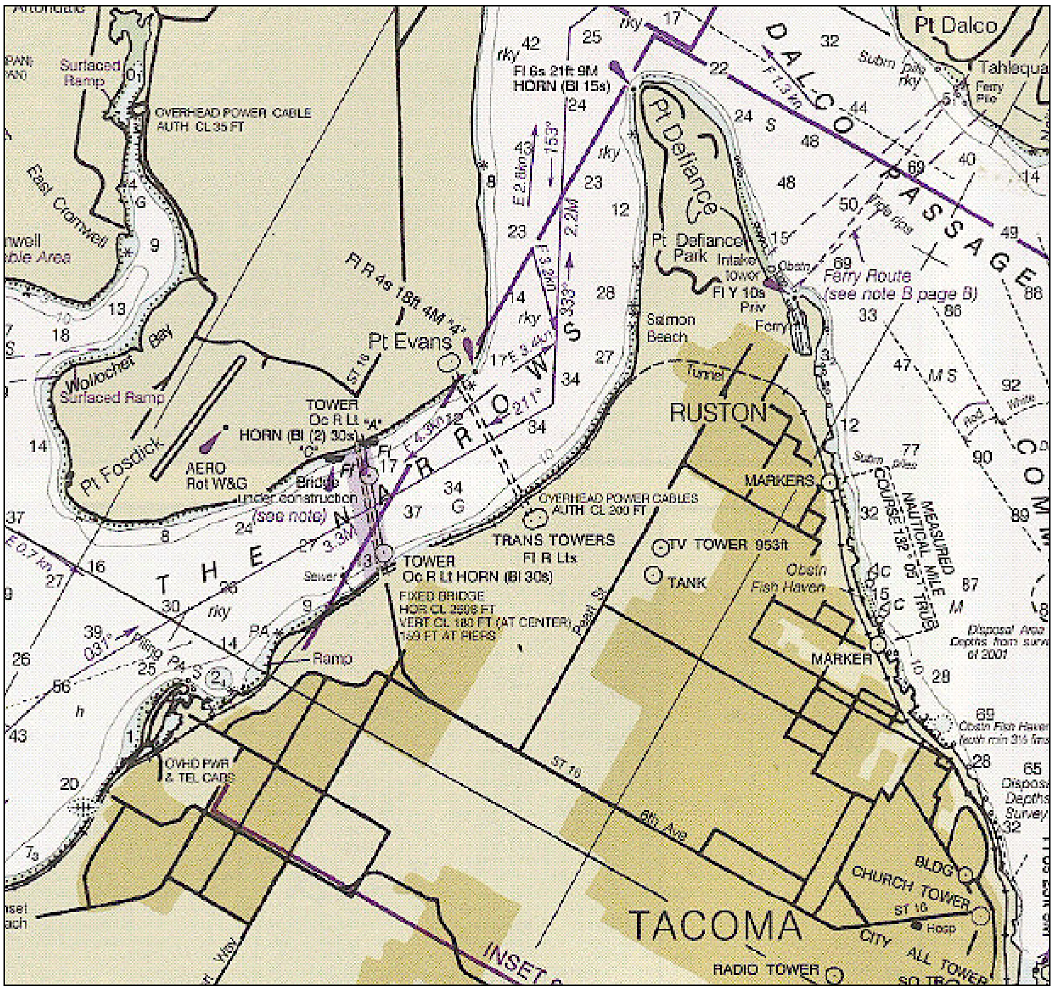


Southern Puget Sound, south of Tacoma Narrows, is an important aquaculture region with a growing population. The water quality in southern Puget Sound is under stress from non-point pollution and other sources. [1] Water flow through the Tacoma Narrows directly affects water quality in southern Puget Sound.

[1] State of the Sound 2007. Puget Sound Action Team, Washington Office of the Governor, Olympia. http://www.psat.wa.gov/Publications/state_sound07/sections/2007_stateofthesound_executive.pdf

The Tacoma Narrows is a commercial shipping channel regularly used by large ships, tugboats and barges (Figure 4). It is also used for sport and commercial fishing, particularly by Native Americans with traditional area fishing rights, and for recreational scuba diving. Whales (grey and orca) and other marine mammals (seals, sea lions, dolphins) pass through occasionally. Salmon migrate through the area. Along the shorelines are many homes with views of the Narrows.

Figure 4: Tacoma Narrows Nautical Chart



The area has been the subject of many physical studies associated with the new Tacoma Narrows Bridge project, including geophysical and current studies. Environmental studies in the area are relatively limited, although the baseline species composition and water quality is well-known. The tidal currents in the Narrows are strongest at Point Evans, northeast of the bridge and in clear view of over 90,000 people who drive every day across the bridge. Figure 5 shows "vital statistics" for the Tacoma Narrows.[2]

[2] EPRI TP-006-WA, Washington Tidal Power System Level Design

Figure 5: Tacoma Narrows Site Characteristics

Site	
Channel Width	1,490 m
Average Depth (from MLLW)	42 m
Deepest Point	68 m
Maximum Tidal Range	5 m
Seabed Type	Dense sand and gravel
Tidal Energy Statistics	
Depth Averaged Power Density	1.7 kW/m^2
Average Power Available	106 MW
Average Power Extractable (15%)	16 MW
# Homes equivalent (1.3 kW/home)	11,000
Peak Velocity at Site	3.9 m/s
Interconnection	
Pilot Plant	Connection to existing distribution line at 12.47kV
Commercial Plant	Connection to new 115kV substation at 33kV
Nearest Port	Port of Tacoma (20 km)

1.3 EPRI Ocean Energy Study

In 2004-6 the Electric Power Research Institute (EPRI) conducted a national study of tidal and wave energy potential for renewable power generation in the USA.[3] The study included development of standard or system-level protocols for analysis, reviews of environmental and regulatory issues and technologies, and specific site assessments where the protocols were applied.

The protocol and review reports from EPRI include:

- TP-001-NA Rev 3, *Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices*
- TP-002-NA Rev 2, *Economic Assessment Methodology*
- TP-004-NA, *Survey and Characterization of Tidal In-Stream Energy Conversion (TISEC) Devices*
- TP-005-NA, *Methodology for Conceptual Level Design of TISEC Plant*
- TP-007-NA, *Tidal Power Environmental and Regulatory Issues Report*
- TP-008-NA, *Tidal Power Final Summary Report*

EPRI visited regions around the USA to discuss ocean energy opportunities with stakeholders, in particular with energy utilities. EPRI initiated its discussions about ocean energy in Washington State in early 2005. Tacoma Power was a participant and encouraged a focus on Tacoma Narrows.

[3] http://archive.epri.com/oceanenergy/streamenergy.html

1.4 Tacoma Power's Consideration of Tidal Energy Potential

The generation of electric power for commercial sale in the USA is regulated by the Federal Energy Regulatory Commission (FERC). The FERC grants licenses for power projects following a complex process of studies and stakeholder consultations.[4] The process begins when an applicant files a Preliminary Permit application to develop a site. If granted, the preliminary permit gives the applicant the exclusive right for three years to study the site and obtain necessary permits. After three years the applicant must then file a commercial license application for the project with FERC. Filing a preliminary permit application is free and of minimal difficulty.

After negotiations with Washington stakeholders in 2005, including Tacoma Power, EPRI agreed to conduct a study of tidal power generation feasibility in the Tacoma Narrows. On September 15, 2005 Tacoma Power submitted an application to the Federal Energy Regulatory Commission (FERC) seeking a preliminary permit for the development of a tidal energy project in the Narrows. The FERC issued the preliminary permit on February 22, 2006.

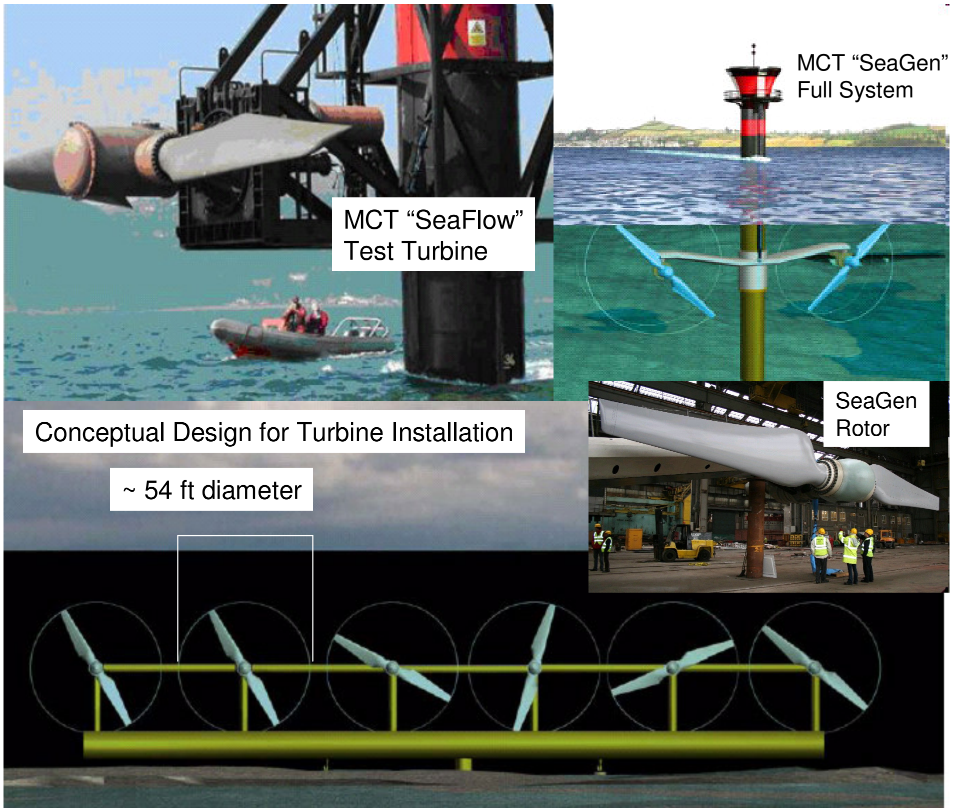
Working with available information, EPRI completed a concept level evaluation of possible tidal turbine installation sites, technologies, and cost estimates for both a pilot installation and a future commercial-scale plant. The study did not consider environmental studies or permit requirements. EPRI published the results in EPRI TP-006-WA, *Washington Tidal Power System Level Design.*

For a much better understanding of this report, the reader should first review the EPRI Tacoma Narrows study.[5] It has detailed descriptions, evaluations, and calculations of all the topics covered in this report. That information will not be duplicated in this report except in summary form needed for context and comparison to this report's conclusions.

To estimate turbine power and cost, EPRI used the "SeaGen" tidal turbine being developed by Marine Current Turbines Ltd. (MCT) of the UK. One of the few tidal turbines actually constructed and being operated today, it is also the largest. MCT designed a piling installation on which the two 16m / 54ft rotors are raised and lowered by an elevator chassis so the turbines can be maintained out of the water (Figure 6). However, this is not a fundamental requirement, and the turbines could be installed fully submerged, depending on development of a suitable technology.

Figure 6: MCT SeaGen Tidal Turbine

[4] EPRI TP-007-NA, Tidal Power Environmental and Regulatory Issues Report
[5] http://archive.epri.com/oceanenergy/attachments/streamenergy/reports/TP-006-WA_Design_Feasibility_Report_010106.pdf



The Seagen prototype is rated at 600kW x 2 at a current of 2.4m/s (with 16m diameter rotors). Average power production is about half that amount, therefore one 16m rotor would produce on average about 300kW where the "rated" current speed is 2.4 m/s or 5 knots.[6] At slower current speeds the power production drops dramatically. For example, at 1.5 m/s the power output would be about 20% of the power at 2.5 m/s, or about 60kW (using basic analysis).

EPRI concluded that a commercial plant of 64 double-rotor turbines (the equivalent of 128 "normal" turbines) might cost about $103 million, with operating costs of about $3.8 million. Estimated average output is 16 MW (Figure 7). This would result in nominal cost of energy for a municipal generator of about 8.4 cents per kW, assuming the application of incentives similar to other renewable energy sources. The cost estimate did not include permitting or environmental studies. EPRI was clear that their estimates were based on best available information and include many simplifications and assumptions that are unproven. Most importantly, EPRI concluded that the cost of renewable tidal power from Tacoma Narrows could be competitive with other renewable sources such as wind power if indeed the assumptions are realized.

Figure 7: EPRI Tidal Power Plant Design for Tacoma Narrows

[6] Personal communication, Peter Frankel, MCT Ltd, Sept 11, 2007.

Array Performance	
Number of turbines	64
Number of transects	5
Availability	95%
Transmission Efficiency to Shore	98%
Capacity Factor	30%
Average Extracted Power	16 MW (16 MW extraction limit)
Average Electric Power	13.7 MW
Maximum Electric Power	45.8 MW
Annual Electricity Generation	120,000 MWh

Using the EPRI information, Tacoma Power organized its approach in four Phases:

Phase 1: EPRI conceptual study
Phase 2: Feasibility study using detailed data and permitting information
Phase 3: Pilot project
Phase 4: Commercial scale project

In September 2006 Tacoma Power issued a public Request for Proposals to proceed to Phase II, a feasibility study (resulting in this report). The RFP asked for additional information regarding emerging technologies such as various in-stream generation units, as well as further investigation of current models, analysis of the assumptions made in the EPRI study, identification of additional tasks necessary for site selection, and more detailed information on the permitting and environmental issues involved with tidal energy. The final section would create project economic and construction cost estimates for a pilot installation and commercial installation.

Tacoma Power evaluated bids from four competing teams and selected Puget Sound Tidal Power LLC (PSTP) to assist with the project. At the same time, Tacoma Power received a grant from the Bonneville Power Administration to support the study costs. PSTP received its Notice to proceed in March 2007. The grant specified dates for accomplishing the study and its conclusion in November 2007.

1.5 Study Consortium

PSTP is a Washington company formed in 2006 specifically to help develop ocean energy projects. The founder, Burton Hamner, has over 20 years experience in coastal zone management throughout Puget Sound, including environmental permitting, technology analysis, and marine sciences expertise.

PSTP assembled a team of local firms and experts for the study, including:

- **Evans-Hamilton, Inc**., Seattle: Oceanographers who conduct field current measurements in Tacoma Narrows.

- **Coast and Harbor Engineering, Inc**., Edmonds, WA: Hydraulic and marine structural engineers who model the currents in Tacoma Narrows, determine the turbine sites and power potential, and estimate turbine and cable installation costs.

- **Meridian Environmental, Inc**., Seattle: Environmental permitting and FERC licensing consultants who estimate the permitting requirements and costs and develop FERC licensing strategies.

- **Williamson and Associates, Inc**, Seattle: Ocean survey and marine engineers who develop the costs for site surveys.

- **Manson Construction Company**, Seattle: Marine construction contractors who estimate turbine installation and maintenance costs.

- **BioSonics, Inc**., Seattle: Fisheries hydroacoustics experts who design a monitoring system to detect fish, marine mammals, and flotsam around tidal turbines and the entire site.

- **Resource Dimensions, Inc**, Gig Harbor, WA: Economists who develop the cost of energy for the commercial project concept.

From the **University of Washington**:

- Prof. Mitsuhiro Kawase, Physical Oceanography: Input to and review of current modeling and development of a research workshop proposal that will initiate estuary-wide studies of tidal power generation and its cumulative impacts.

- Prof. Bruce Adee, Mechanical Engineering and Naval Architecture: Review of tidal turbine technologies and assessment of applicability to the Tacoma Narrows.

- Prof. Kai Strunz, Electrical Engineering: Review of turbine generator technologies and future trends.

1.6 Project Management

PSTP was the general contractor for the study. The project tasks were accomplished concurrently whenever possible (Figure 8). All team members were given a study period in which to review the EPRI system-level reports and other references. A reference library of relevant academic and scientific literature was prepared on CD-ROM and provided to the team members.

Figure 8: Project Schedule

2007	April	May	June	July	Aug	Sept	Oct	Nov
Data review								
Field data								
Current model								
Power model								
Tech review								
Permit analysis								
Monitoring design								
Construction costs								
Economics								

The project was organized into three Stages according to the BPA's grant requirements. Each included a Stage Gate that required passage before the subsequent stage was authorized to proceed. Stage Gate 1 comprised power evaluation - is there really enough tidal power in Tacoma Narrows to generate the turbines, and if so, where? Stage Gate 2 was composed of the technology - what is the feasibility of technology to generate tidal power? Stage Gate 3 was the final conclusion - what is the expected economic cost and benefit to the region?

Because project teams worked on simultaneous tasks, one dependency became clear: tthe need to match turbine technology to the specific sites. For example if the site was shallow, the largest proposed turbines wouldl not fit. If the site had substantial shear currents (off axis of the main line of flow), then turbines composed of significant fixed structures such as ducts would have severe side loads which would increase their construction cost. Future projects would benefit from this lesson in understanding site physics and conditions before selecting technologies for further study.

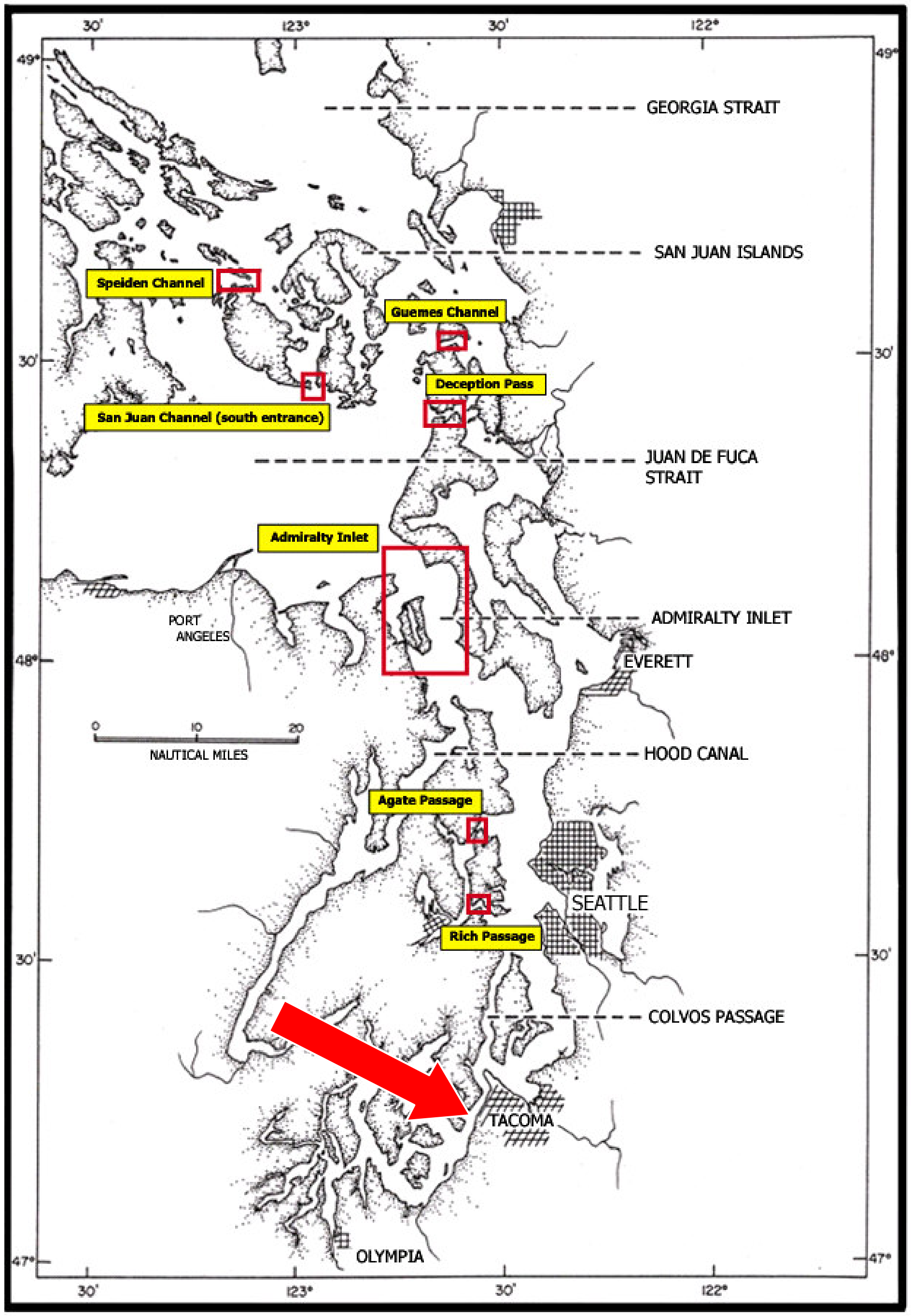
1.7 Significant Developments During the Project

Other Tidal Project Sites Proposed in Puget Sound

Soon after Tacoma Power filed its FERC preliminary permit application, the Snohomish Public Utility District (SnoPUD), located north of Tacoma and also on the shoreline of Puget Sound, filed seven preliminary permit applications for tidal power projects.

The largest of the SnoPUD sites is Admiralty Inlet, at the entrance to Puget Sound. Tacoma Narrows is "downstream" and inside the estuary from Admiralty Inlet (Figure 9). Two other sites at Rich Passage and Agate Pass are also inside the estuary. Extraction of tidal energy from the Inlet will have effects on all flows in the enclosed estuary and will have implications for any project in Tacoma Narrows. At this time SnoPUD is evaluating its sites and has made no commitments to site development.

Figure 9: Tidal Power Sites Proposed in Washington



If SnoPUD decides to proceed with tidal power development, this will have significant implications for the Tacoma Power project. Tidal turbines reduce the flow passing through them during the energy extraction process. If enough turbines are introduced into the currents, they will change the currents and the biological systems that depend on them. Obviously, there is a limit to the number of turbines that can be introduced into a closed system like Puget Sound. With more than one project proposed, clearly a Sound-wide study of the total tidal turbine potential and limits is needed.

Tacoma Power can best preserve its options by establishing its intention for a certain amount of power production and energy extraction before any other entities do so. However, this will not stop the authorities from requiring a cumulative effects study if another entity such as SnoPUD decides to develop tidal power in Puget Sound.

FERC Pilot Project License Option

In September 2007, the FERC announced a new license option designed to allow hydro-kinetic and other technologies to generate commercial power on a pilot project basis. The license is good for five years and allows generation and sale of up to 5 MW/hr. But projects must be completely removable if environmental concerns warrant it, thereby limiting physical changes to geography and excluding dams or impoundments or large concrete structures, which would not be allowed. One concern is whether pilings driven into the seabed would be allowed since they are difficult to remove and are usually cut off at the base to be removed. Options for Tacoma Power to respond to this new development are discussed in the Permitting analysis.

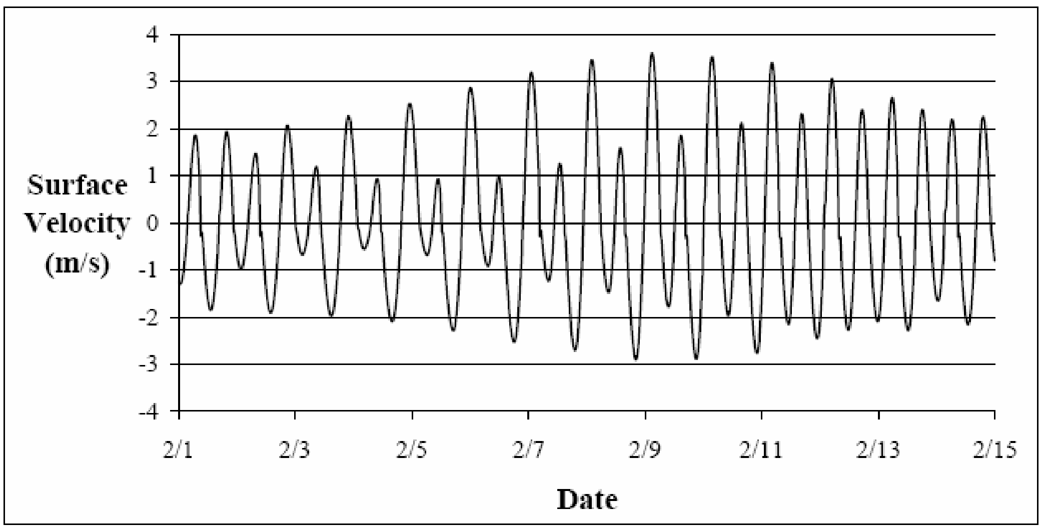
2 Tidal Power Basics

The tides at Tacoma Narrows reverse direction twice a day. These are periods of no power generation. Because tidal flows are driven mostly by lunar gravity, they are highly predictable. For a given site, the tidal current velocity can be predicted with great accuracy up to 30 years in advance for any time of day.

An extensive discussion of the physics of tides and tidal flows is provided in EPRI TP-001-NA Rev 3, *Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices*

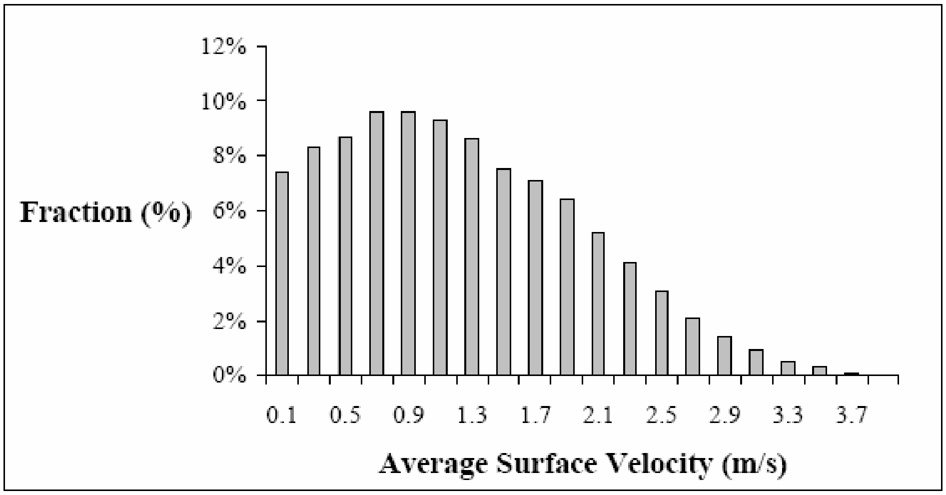
Figure 10 illustrates the cyclical flows of the tides in Tacoma Narrows.

Figure 10: Tidal Cycle Variation at Point Evans, Tacoma Narrows, Feb 1-14, 2005 [7]



[7] EPRI Tacoma study

Figure 11: Histogram of Current Velocity Frequencies at Point Evans, Tacoma Narrows



A frequency distribution graph makes it clear that high velocities suitable for tidal power generation do not happen frequently in tidal cycles (Figure 11). The graph shows that velocities exceed 2 m/s only about 20% of the time.

The power of the tidal flows depends on their velocity. The power is calculated as the cube of velocity. A simple rule of thumb is that the power per square meter in kilowatts (kW) is ½ times the velocity cubed. Therefore a flow of 2 meters per second (m/s) has $0.5 \times 2^3 = 4$ kW/m^2 (Figure 12).

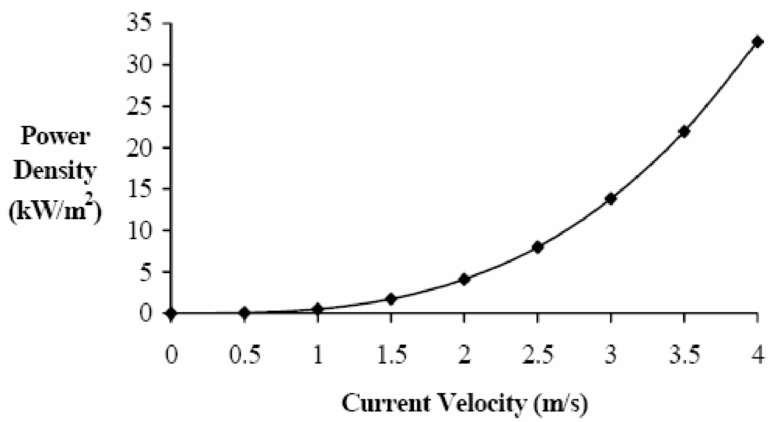
Figure 12: Power Density of Flowing Water [8]

The instantaneous power density of a flowing fluid incident on an underwater turbine is given by the following equation:

$$\left(\frac{P}{A}\right)_{\text{Water}} = \frac{1}{2}\rho U^3 \qquad \text{(watts per square meter)}$$

where A is the cross-sectional area of flow intercepted by the device, i.e. the area swept by the turbine rotor (in square meters), ρ is water density (in kilograms per cubic meter; 1,000 kg/m^3 for freshwater and 1,025 kg/m^3 for seawater) and U is current speed (meters per second). For tidal currents, U varies with time in a predictable manner as described previously, and also depends on depth beneath the water surface and position in the channel, as will be described later.

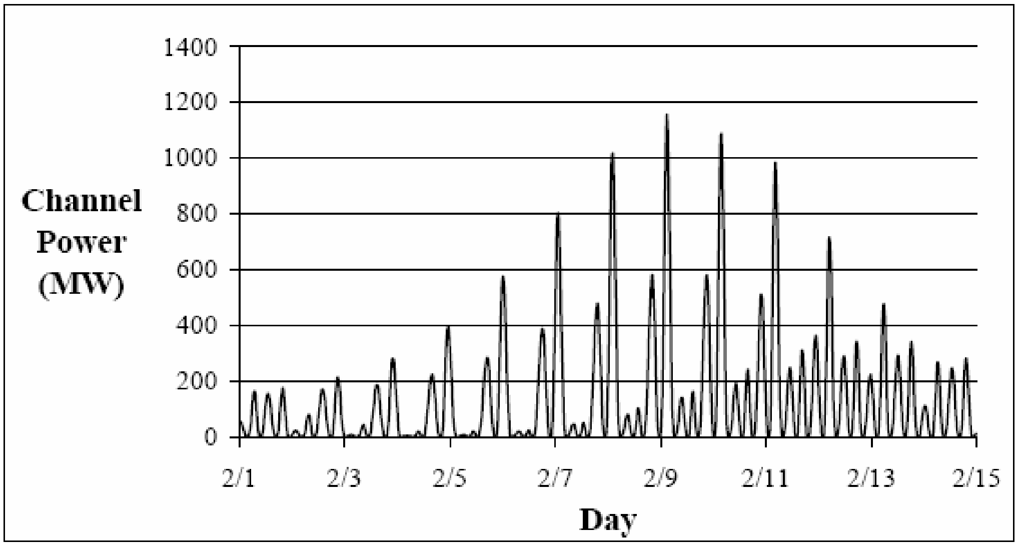
Because power density varies with the cube of current velocity, it increases quite rapidly with current speed as shown in Figure 1-6.



When we combine the tidal cycle with the power density curve, we see that the power density of the tides varies tremendously across the tidal cycle.

[8] EPRI TP-001-NA Rev 3, Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices

Figure 13: Channel Power at Point Evans in MW



The power available to a tidal turbine depends on its swept area – the area physically blocked by the turbine rotor. The swept area in m^2 is multiplied by the power in kW/m^2 to determine the power available to the rotor. So in a 2 m/s current with = 4 kW/m^2, a rotor with 10 m^2 swept area would have available power of 10x4 or 40 kW.

Figure 14 shows the power density available to rotors of different diameters at different current velocities.

Figure 14: Power Density for Swept Area of Turbines

Power Density of Water Currents in kW/hr

		VELOCITY m/sec						
Diam (	**Area (m^2)**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**
1	*1.0*	0.5	1.7	4.0	7.8	13.5	21.4	32.0
2	*3.1*	1.6	5.3	13	25	42	67	101
3	*7.1*	3.5	12	28	55	95	152	226
4	*12.6*	6.3	21	50	98	170	269	402
5	*19.6*	9.8	33	79	153	265	421	628
6	*28.3*	14	48	113	221	382	606	**905**
7	*38.5*	19	65	154	301	520	825	1,232
8	*50.3*	25	85	201	393	679	**1,078**	1,608
9	*63.6*	32	107	254	497	859	1,364	2,036
10	*78.5*	39	133	314	614	1,060	1,684	2,513
11	*95.0*	48	160	380	742	1,283	2,037	3,041
12	*113.1*	57	191	452	884	1,527	2,425	3,619
13	*132.7*	66	224	531	**1,037**	1,792	2,845	4,247
14	*153.9*	77	260	616	1,203	2,078	3,300	4,926
15	*176.7*	88	298	707	1,381	2,386	3,788	5,655
16	*201.1*	101	339	804	1,571	2,714	4,310	6,434
17	*227.0*	113	383	908	1,773	3,064	4,866	7,263
18	*254.5*	127	429	**1,018**	1,988	3,435	5,455	8,143
19	*283.5*	142	478	1,134	2,215	3,828	6,078	9,073
20	*314.2*	157	530	1,257	2,454	4,241	6,735	10,053

The highlighted cells show the point at which a megawatt (MW) of power is available. But the power must be extracted by the turbine. An average efficiency for tidal turbine rotors, as reported by developers and estimated from test results, is about 35%. Thus to estimate power produced by the turbine the available power density is multiplied by the efficiency. Figure 15 shows the power output of a turbine with 35% efficiency at a range of diameters and current velocities.

Figure 15: Power Output of Turbine with 35% Efficiency

			Power Output of 35% Efficient Turbine in kW						
			VELOCITY m/sec						
Diam (	**Area (m^2)**	**Efficiency**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**
1	*1.0*	*35%*	0.2	0.6	1.4	3	5	8	11
2	*3.1*	*35%*	0.5	2	4	9	15	24	35
3	*7.1*	*35%*	1.2	4	10	19	33	53	79
4	*12.6*	*35%*	2.2	7	18	34	59	94	141
5	*19.6*	*35%*	3.4	12	27	54	93	147	220
6	*28.3*	*35%*	5	17	40	77	134	212	317
7	*38.5*	*35%*	7	23	54	105	182	289	431
8	*50.3*	*35%*	9	30	70	137	238	377	563
9	*63.6*	*35%*	11	38	89	174	301	477	713
10	*78.5*	*35%*	14	46	110	215	371	589	880
11	*95.0*	*35%*	17	56	133	260	449	713	**1,064**
12	*113.1*	*35%*	20	67	158	309	534	849	1,267
13	*132.7*	*35%*	23	78	186	363	627	996	1,487
14	*153.9*	*35%*	27	91	216	421	727	**1,155**	1,724
15	*176.7*	*35%*	31	104	247	483	835	1,326	1,979
16	*201.1*	*35%*	35	119	281	550	950	1,509	2,252
17	*227.0*	*35%*	40	134	318	621	**1,072**	1,703	2,542
18	*254.5*	*35%*	45	150	356	696	1,202	1,909	2,850
19	*283.5*	*35%*	50	167	397	775	1,340	2,127	3,176
20	*314.2*	*35%*	55	186	440	859	1,484	2,357	3,519

The use of a diffuser can increase efficiency to about 60% for the same swept area. Turbines with diffusers would therefore make a little less than double the energy shown in the table.

This is a very important table for Tacoma Power to consider. The velocity in Tacoma Narrows is less than 2 m/s about 80% of the time. Thus a 10m diameter turbine, about 34 feet tall, would make less than 100 kW output 80% of the time and even less than that on average. To make 10 MW average output over a hundred,10m turbines would be needed. In comparison, the new generation of wind turbines are rated at 3 MW output with 30% capacity factor, making about 1 MW on average. To make 10 MW average output approximately ten wind turbines are needed.

Tidal turbine developers have been claiming outputs of about 1 MW for their turbines. Upon review we see that they are using high maximum velocities, 3-4 m/s, for their “rated” power estimates. Large tidal channel flows with such velocities are found in only in a few places around the world, typically around 40-60 degrees north and south where there are high tide elevation changes of 20 feet or more.

3 Tidal Power in Tacoma Narrows

3.1 Objectives and Outcomes

To pass Stage Gate 1 of the project, Tacoma Power needed to determine if the tidal currents in the Narrows really do have sufficient power and exactly where the power is so turbine sites could be located. A computer model and field data to validate the results were needed for the measurements.

This work includes reviewing the existing hydraulic and bathymetric data, collecting new hydraulic and bathymetric data, generating a model of the Tacoma Narrows from the gathered data, identifying tidal power manufacturers and analyzing the data to make a go/no-go decision concerning tidal power generation in the Tacoma Narrows.

The outcome is there is less power available than was predicted by the EPRI estimate. The power is concentrated around Point Evans in relatively shallower waters to 20m depth compared to 50m+ depth in the central channel. The greatest power density is about 3.4 kW/m^2. In comparison, in the central channel, the average power is about 1.5 kW/m^2.

To estimate the maximum power available to turbines in a commercial plant array, a conceptual 10m-diameter propeller-type turbine was used. 176 turbine sites were specified on 13 transects across the Point Evans site. Power density available to each turbine's swept area of 78 m^2 was calculated from the current model. The total power available to the turbine array is 326,075 MWhr/yr. If this power can be captured at 30% efficiency, it would produce about 98,000 MWhr/yr or 11 MW/hr on average.

The EPRI study estimated power potential of 16 MW/hr from its conceptual array. That array used 128 turbines of diameter 16m (with 2.5 times the area of 10m turbines) located in the central channel, and assumed power density of 1.7 kW/m^2, which is confirmed by this study's measurements. The results of this study and the EPRI study are of the same order of magnitude with differences because EPRI used larger turbines in an area with lower power.

The estimated output of 11 MW should be compared to other sources. As shown in the introduction, the average power of 46 commercial wind projects in Washington and Texas is rated at 117MW with capacity factor of 40% or 47 MW. Therefore the power output of the tidal power array would be about 25% of an "average" wind turbine array. The new wind turbines are rated at 2 MW or higher, generating 800 kW+ on average assuming 40% capacity. In comparison, the 176 turbines in the tidal power array would produce 100-400 kW each depending on location and assumed efficiency.

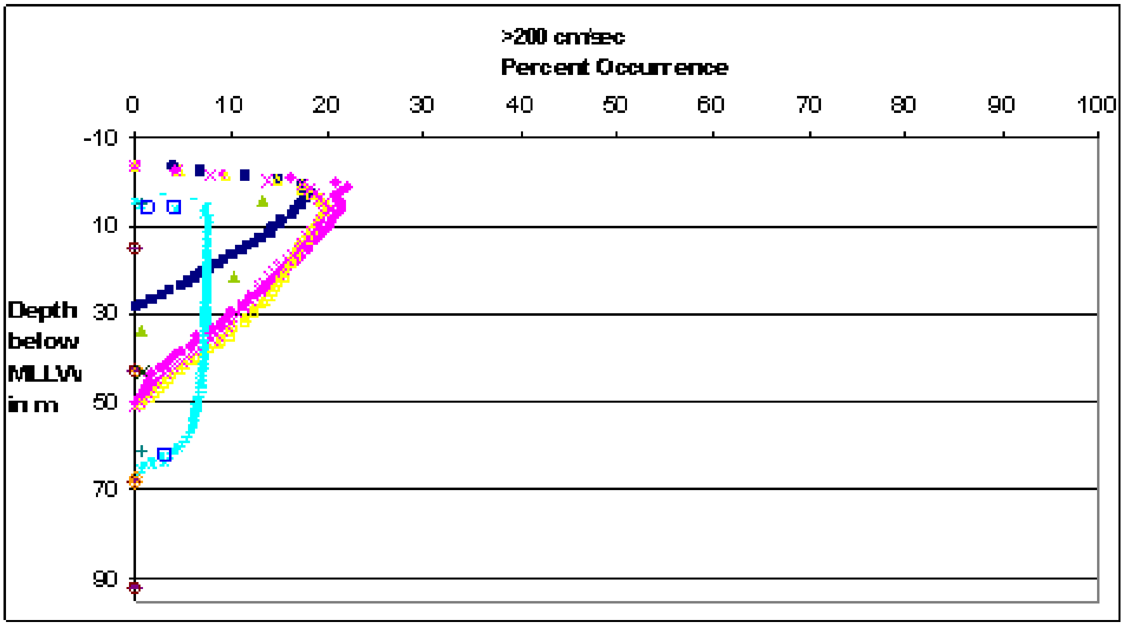
3.2 Field Measurement Report

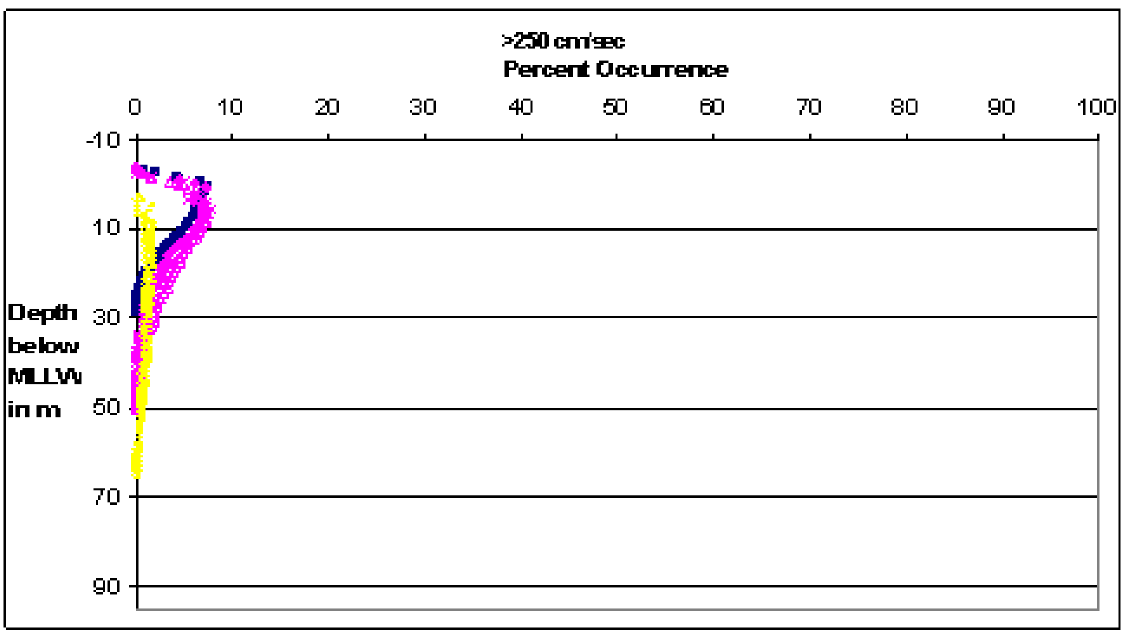
As a first step toward evaluating the economic, engineering, and permitting feasibility of a tidal energy facility located with the Tacoma Narrows, Evans-Hamilton, Inc. (EHI) assessed historical current records and collected new current records. The data report covers historical current measurements primarily from 1977 – 1980 and new current measurements for 30 May 2007 to 3 August 2007. The report describes the instrumentation, data processing methods, and resultant data collected both for the historical and new measurements. The complete report is attached as Appendix 1.

A finding of particular significance is that the velocities in Tacoma Narrows exceed 2 m/s only about 20% of the time, and exceed 3 m/s hardly ever. The review of tidal turbine technologies shows that most of them are designed for rated power at 3 m/s or more. Expected output of these turbines in Tacoma Narrows will thus be significantly less than the rated power.

Figure 15 shows the percent occurrence for current velocities of 2 m/s and 2.5 m/s at different depths (in meters) from historical and field measurements. Important conclusions are that the high velocities with the most power are uncommon, and they occur relatively far up in the water column. This second factor will also affect tidal turbine output. To allow for navigation clearance the top of a turbine should be at least 5 m below the surface outside of the shipping channels, and at least 15 m below surface in the shipping channel. If the turbine is 10 m in diameter its hub must be at least 10 m deep outside the shipping channel and 20 m deep in the shipping channel. At these depths the high velocity frequencies are significantly reduced and turbine output will also be reduced.

Figure 15: Percent Occurrence of High Velocity Currents in Tacoma Narrows



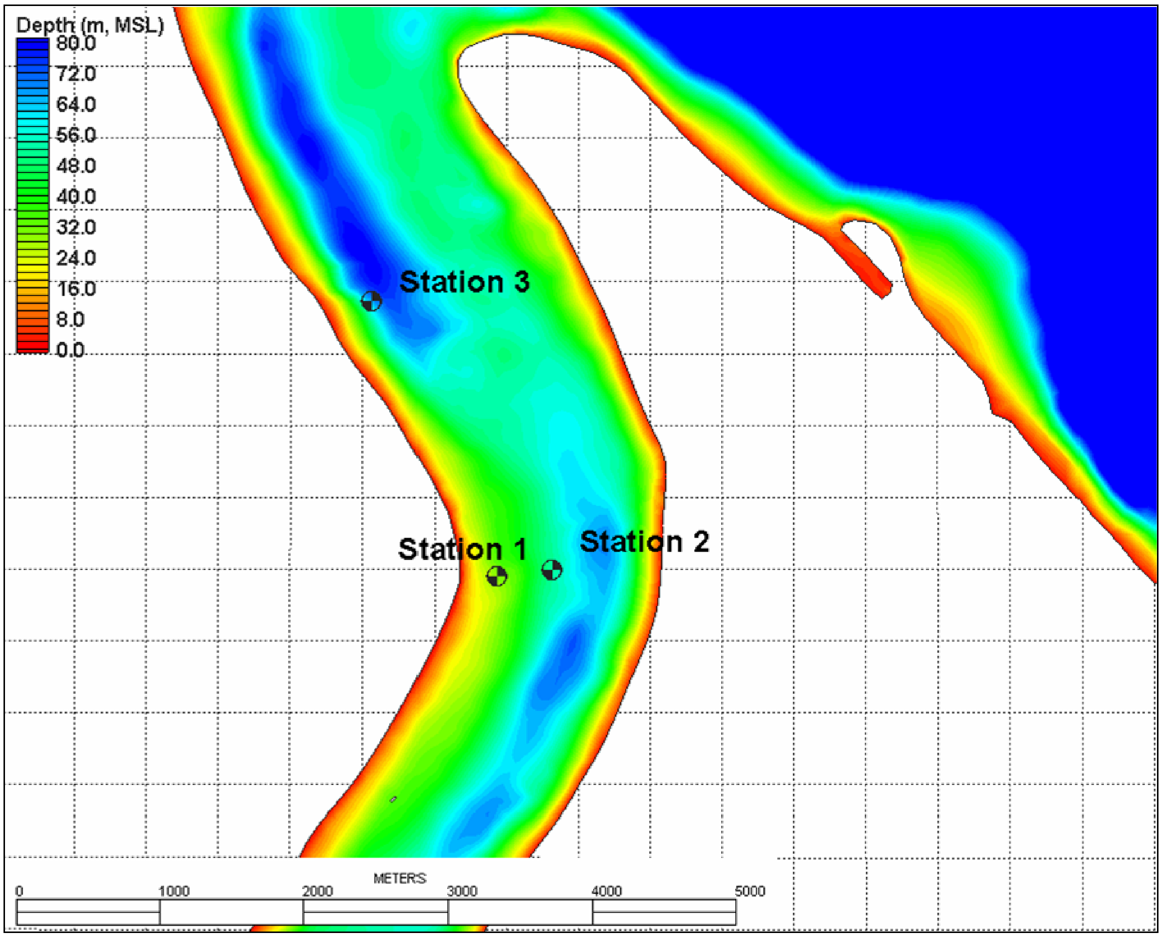


3.3 Current Modeling

(Note: This section is largely based on the Tacoma Power Stage Gate 1 report to BPA, authored by Scott Amsden, Tacoma Power project manager).

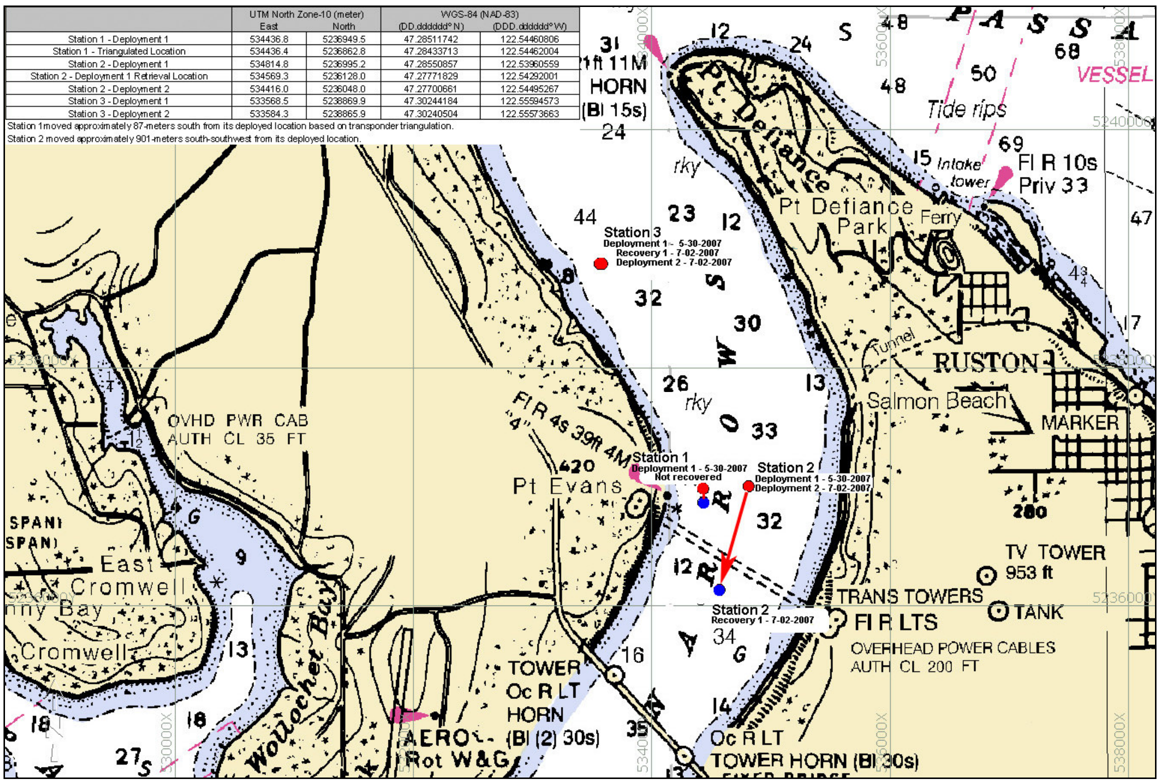
The first step in reviewing and analyzing the existing hydraulic data for Tacoma Narrows was completed in early May of 2007. From this data, and an exploratory trip into the Tacoma Narrows, the best locations were selected to place Acoustic Doppler Current Profilers (ADCP) (see Figure 16). Station 1 was chosen because the historical data and physically observed currents showed it experienced some of the strongest daily currents. Station 2 was similarly chosen however, it was also chosen to provide current data at a greater depth. Conversely, station 3 was chosen to provide data in an area that experienced some of the more quiescent tidal currents. Data from all three sites provided the necessary data for calibrating a computer model.

Figure 16: Placement location for the three ADCP units



Using three ADCP units provided the minimum amount of data necessary to update and calibrate the Semi-Implicit Eulerian Lagrangian Finite Element (SELFE) model chosen by Dr. Vladimir Shepsis from Coast and Harbor Engineering to model the tidal currents in the Tacoma Narrows. Two trips were made to recover the units and download the data. The first recovery trip was made on July 2, 2007 and the second recovery trip was made on August 2, 2007. Figure 17 shows the location at which the units were recovered and re-deployed. It should be noted that the tidal currents moved station 2 over 900 meters southwest of its original placement location. Station 1 was also moved a short distance to the south. To date, attempts to recover and service the current meter from this site has not been successful due to unknown reasons; however, its location has been pinpointed by means of underwater acoustic ranging. Efforts to retrieve the unit with divers and download its data are on-going. Data from the station 3 ADCP unit was also downloaded during each of the recovery trips into the Narrows.

Figure 17: ADCP placement and retrieval information from Evans Hamilton.



	UTM North Zone-10 (meter) East	North	WGS-84 (NAD-83) (DD.dddddd° N)	(DDD.dddddd° W)
Station 1 - Deployment 1	534436.8	5236949.5	47.28511742	122.54460806
Station 1 - Triangulated Location	534436.4	5236862.8	47.28433713	122.54462004
Station 2 - Deployment 1	534814.8	5236995.2	47.28550857	122.53960559
Station 2 - Deployment 1 Retrieval Location	534569.3	5236128.0	47.27771829	122.5429201
Station 2 - Deployment 2	534416.0	5236048.0	47.27700661	122.5495267
Station 3 - Deployment 1	533568.5	5238869.9	47.30244184	122.5594573
Station 3 - Deployment 2	533584.3	5238865.9	47.30240504	122.5573663

Station 1 moved approximately 87-meters south from its deployed location based on transponder triangulation.
Station 2 moved approximately 901-meters south-southwest from its deployed location.

The data gathered provided information on the magnitude and direction of the tidal currents from a few meters above the ADCP unit to a few meters below the low tide elevation.

Figures 18 and 19 are graphical representations of the data downloaded on July 2nd from station 2. The red line represents the magnitude of the currents during each day of June. The blue lines are vector representations showing both the magnitude and direction of the tidal currents. Although station 2 moved a considerable distance, the unit was equipped with tilt and pressure sensors which allowed the team to determine when the unit was moved so that measurements collected while it moved could be eliminated from the data set. The movement of the mount occurred over approximately one to two days in the middle of the deployment period. The new location of the unit was positioned using acoustic ranging to the acoustic release contained within the bottom mount, combined with DGPS positioning of the vessel using to conduct the ranging. From these data the unit's new position was calculated. This proved valuable because it provided current measurements at an additional location. This data was particularly useful due to the inability to date to recover the unit from station 1 and access those measurements. The unit was recovered in October, after the modeling was completed. The data from the unit is on file; it was not considered necessary to repeat the calibration of the model using that data.

Figure 18: Station 2 data between 2 meters and 27 meters above the ADCP unit

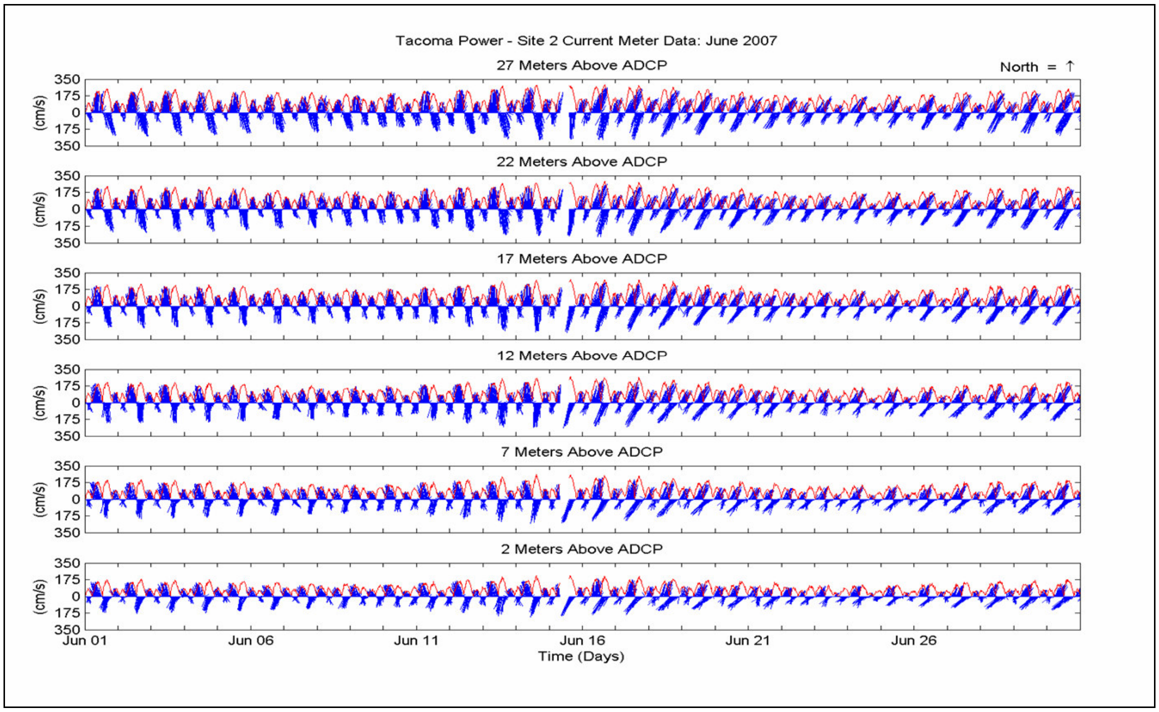
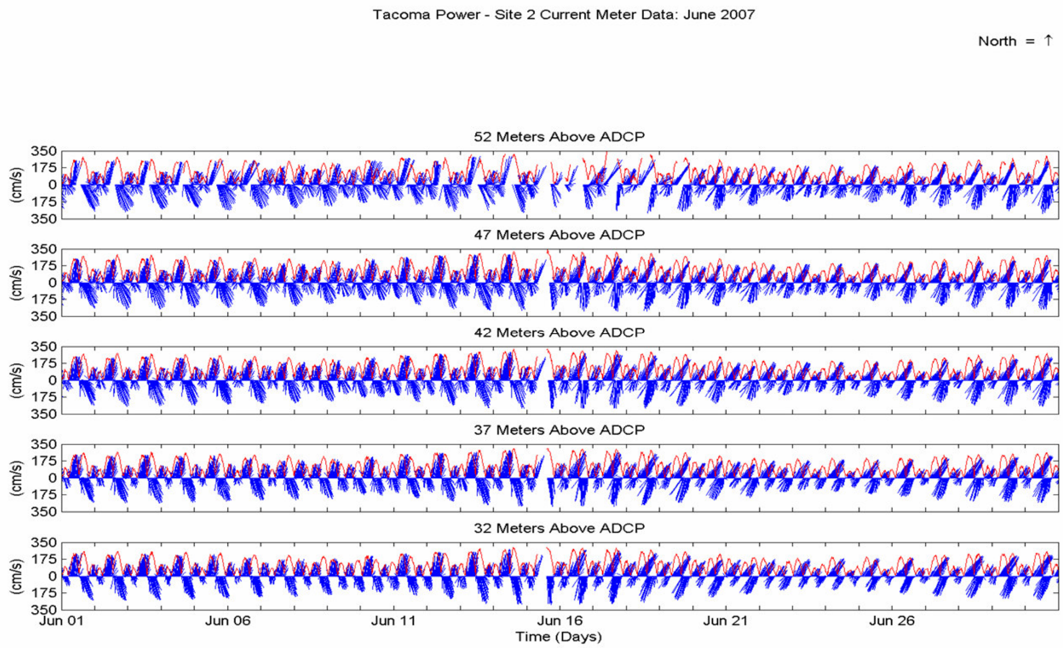


Figure 19: Station 2 data between 32 and 52 meters above the ADCP unit.



The data gathered by the ADCP units was used to update and calibrate the SELFE model. The SELFE model covers the entire Georgia Basin area as well as extending several hundred miles into the Pacific Ocean. Figure 20 shows the extent of the area covered with the SELFE model. Figure 21 is a close-up of the Tacoma Narrows. Each triangle is an individual cell modeled by the SELFE computer model.

Figure 20: Total area modeled by the SELFE computer model.

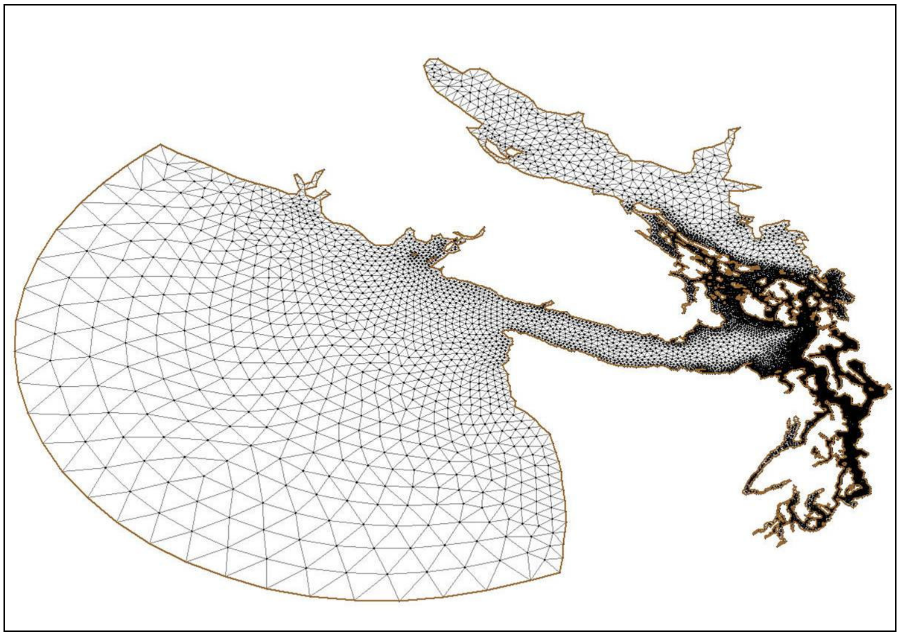
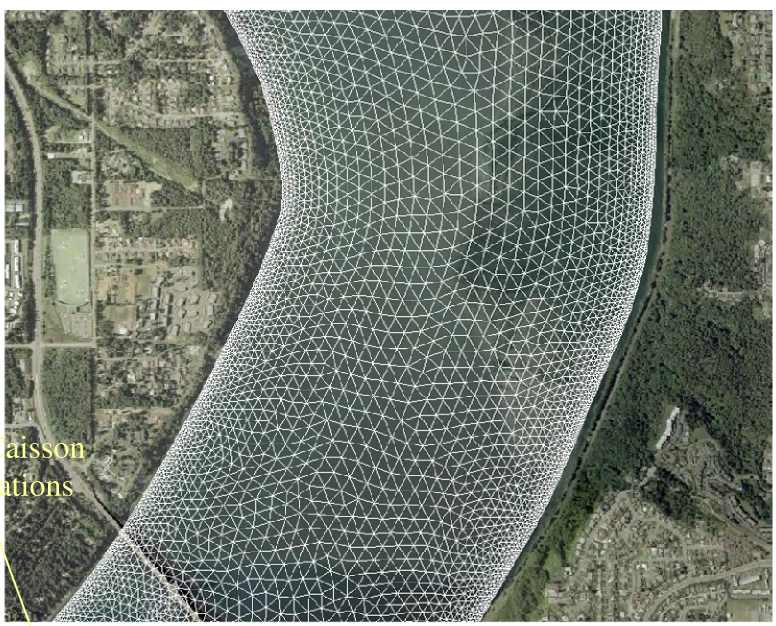


Figure 21: Close-up of the Tacoma Narrows and the cell sizes being modeled.



For each cell, the SELFE model performs calculations to model the tidal currents. In the future, additional modeling calculations can be done on each cell to model the effects of installed equipment. Those effects include changes to current speeds, tidal levels, and water chemistry such as salinity and dissolved oxygen. As one moves into the Puget

Sound, the cells get smaller. This allows the model to account for the effects of the shoreline and bottom contouring on the tidal currents. Figure 20 shows that the effects from the bridge caissons are also taken into consideration.

With the data entered and the individual cells calibrated, the computer model can be run. Figures 22 and 23 show snapshot of the model animation of flood and ebb tide flows in the Tacoma Narrows. The arrows show the current direction. The color represents *depth-averaged* velocity - the highest velocity and most power reaches 3 m/s. The picture is a snapshot - within 60 minutes the picture will be significantly different.

Figure 22: Snapshot of Flood Tide Velocities and Vectors in Tacoma Narrows

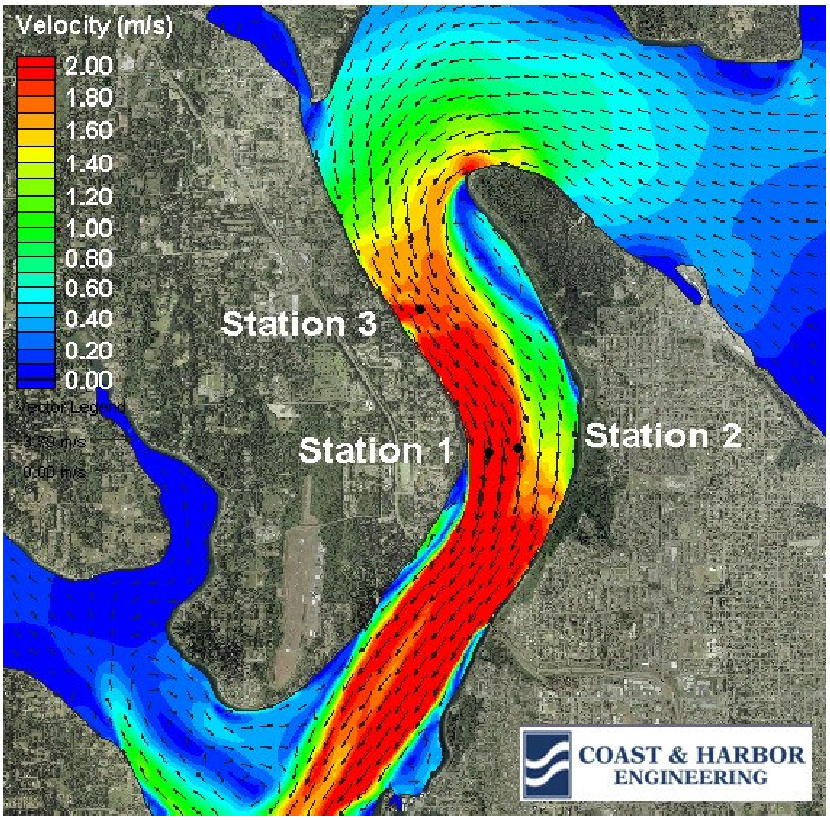
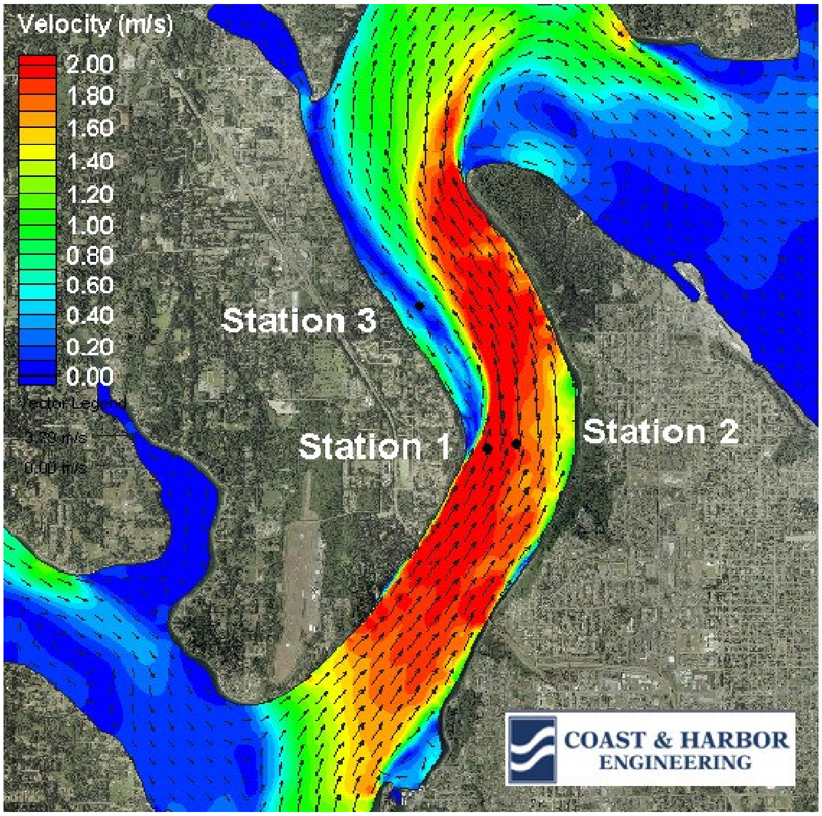


Figure 23: Snapshot of Ebb Tide Velocities and Vectors in Tacoma Narrows



As the currents change direction, large eddies are formed. For a few minutes in each tidal cycle, the Point Evans site can have currents going in opposite directions within less than 100m. This has significant implications for turbine designs: Large turbines in the area of highest energy will experience significant shear forces, perhaps even across their own diameter. Open propeller-type turbines will be the most vulnerable to this highly variable stress loading. Ducted propellers such as proposed by some tidal turbine developers will be less vulnerable, and turbines that either auto-rotate into the current or that have vertical axes of rotation will not be significantly affected.

To develop a concept for a commercial scale tidal power plant, computer runs were made for individual transects or cross sections of the Tacoma Narrows. The density of tidal flow power was calculated using the equation:

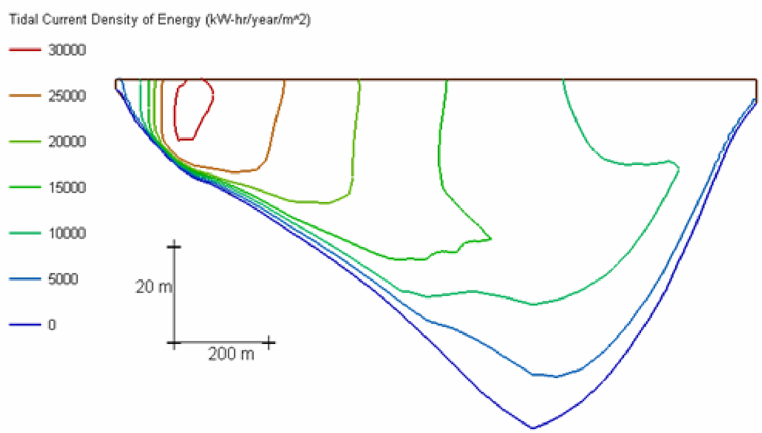
$dP_i = \sum_z 0.5 \cdot \rho \cdot U_z^3 \cdot f_z$ where,

dP_i = Density of tidal current power for each grid element (i) (kW/m2)
ρ = Seawater density (1022-1029 kg/m3)
U_z = Velocity
f_z = Frequency distribution of velocities

This was then used to calculate the density of energy for an entire year using the equation, dE (kW-hr/yr/m2) = dP (kW/m2) * 8,766 (hrs/yr). Contour lines of density are then plotted in the cross section (Figure 24).

Figure 24: Cross sectional contour lines of energy density.

Power Density Range (kW-hr/yr/m^2)	Power (kW-hr/yr)
<5,000	12,220,390
5,000-10,000	112,847,215
10,000-15,000	216,982,917
15,000-20,000	146,717,802
20,000-25,000	110,590,529
25,000-30,000	94,722,880
>30,000	22,553,385



The total power in the channel is calculated in Figure 25.

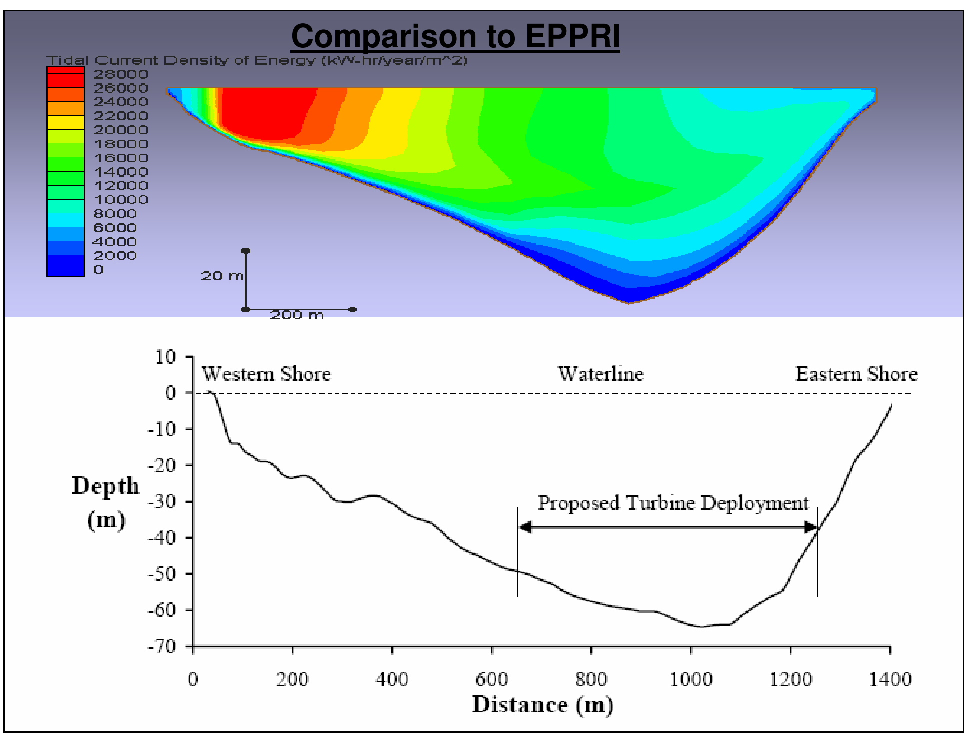
Figure 25: Tacoma Narrows Total Power Density at Point Evans

Tacoma Narrows Total Power Density		
CHE Model		
kWhr/yr/m2	kW/yr	
<5k	12,220,390	
5k-10k	112,847,215	
10k-15k	216,982,917	
15k-20k	146,717,802	
20k-25k	110,590,529	
25k-30k	94,722,880	
>30k	22,553,385	
total	716,635,118	kW/yr
	716,635	MW/yr
	8760	hr/yr
	82	**MW/hr total power**
EPRI Estimate		
avg power	1.7	kW/m2
cross section	63000	m2
	107100	kW
	107	**MW/hr total power**

The difference between the CHE model and the EPRI estimate occurs because EPRI's estimate of 1.7 kW/m2 average power density is higher than actual. If the estimate is 1.3 instead of 1.7 then the EPRI estimate matches the CHE model. EPRI's use of 1.7 as the value is reasonable; only by doing the detailed modeling can the actual values be determined.

In creating the cross sectional plot, it was noted that the strongest energy density did not match the location predicted by EPRI in the concept level feasibility study. This does not mean that this area has low velocity. It does have high velocity but the duration of these high velocities is much shorter than at the shallower (high density) site. EPRI concluded that the best location for construction would be near the deepest portion of the channel because of the large size of the turbines being considered. In Figure 26, EPRI's recommended turbine placement is shown below the cross sectional current density diagram. It clearly shows that the location recommended by EPRI is actually in an area of low energy density. The fact that the best energy is in fact in shallower water is beneficial to Tacoma Power since the possible construction site will not be in the deepest part of the channel which is also the main navigational portion of the Narrows. In addition to avoiding the main navigation channel, the location being close to shore will likely have a positive impact on interconnection costs.

Figure 26: Comparison between current study results and EPRI's proposal.



Power density calculations were run for 13 transects. The approximate location of the transects is shown in Figures 27 and 28. These transects were used for calculations of turbine power extraction and economic analysis.

Figure 27: Location of Transects within Tacoma Narrows

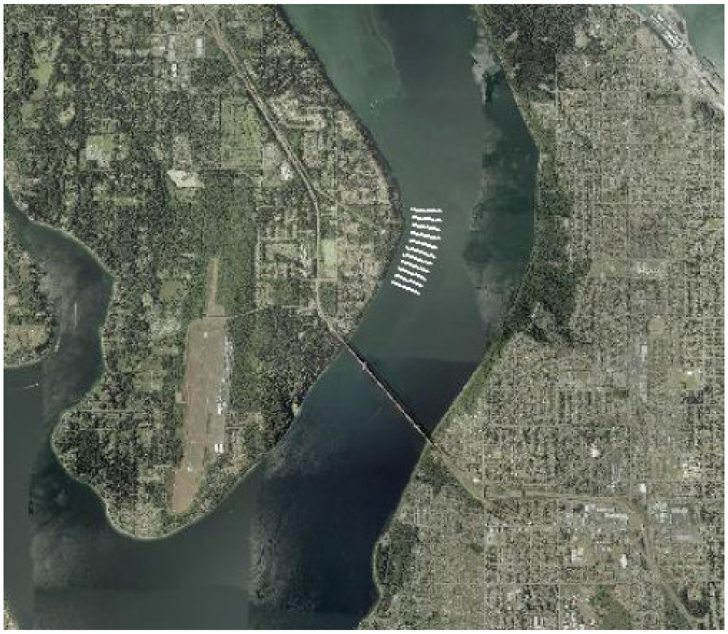


Figure 28: Transect Layout and Turine Sites

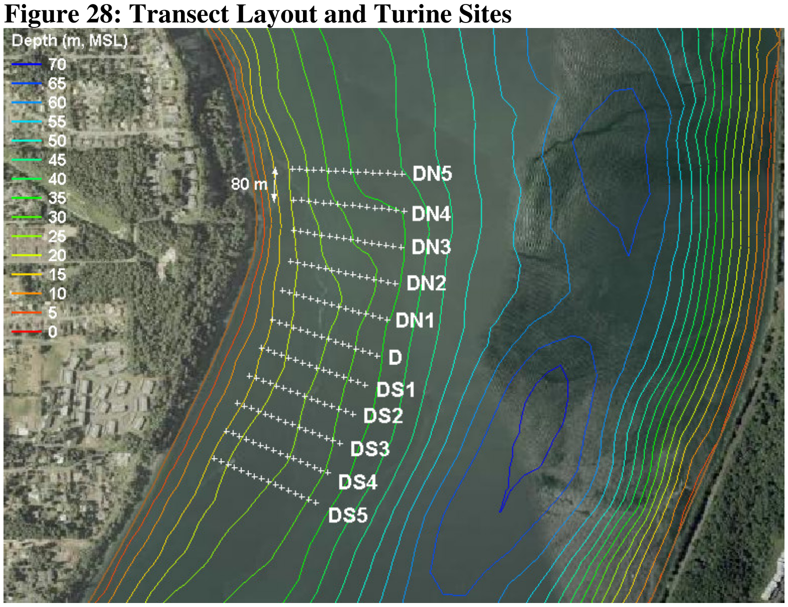


Figure 29 below shows the calculated power density for the transects in Figure 28. It can be seen that, in general, the power density is fairly constant, around 22-24 thousand kWhr/yr, or 2.4-2.7 kW/m^2, in the area being examined.

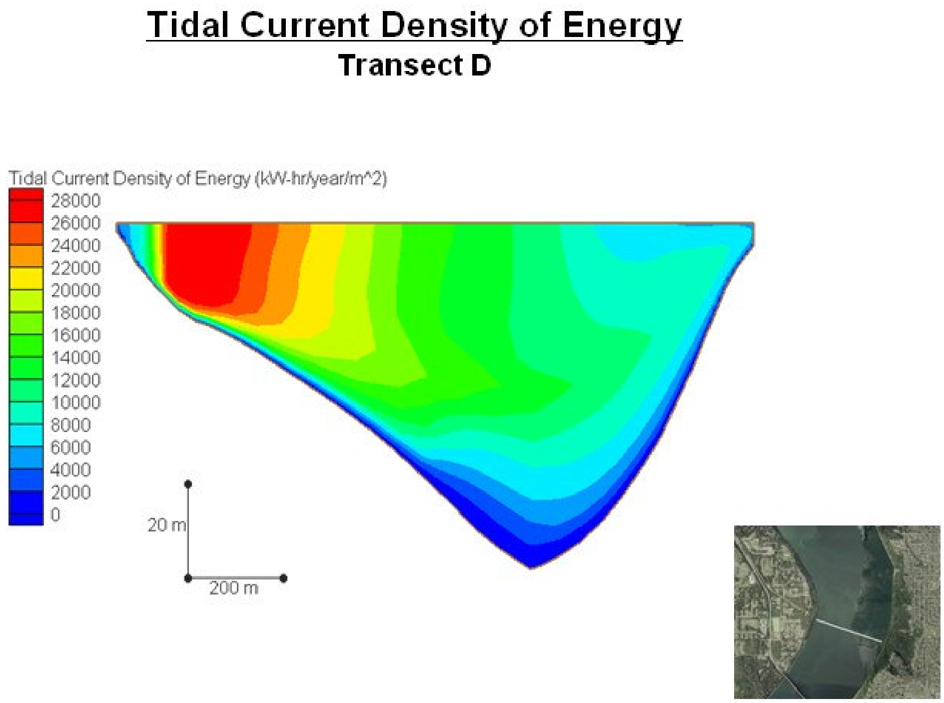
Figure 29: Power Availability for 11m Turbines in a Conceptual Array in Tacoma Narrows

Dist from shoreline (m)	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
Transect																
DN5	21,287	20,699	20,133	19,665	19,537	19,973	20,125	21,123	21,042	21,113	20,835	20,546	20,189	19,760	19,397	18,953
DN4	22,463	22,561	22,125	21,841	21,677	21,960	21,950	22,484	22,247	22,366	21,981	21,590	21,154	20,673	20,257	19,784
DN3	23,592	24,423	24,239	23,919	23,817	23,946	23,775	24,008	23,641	23,364	22,878	22,634	22,118	21,586	21,117	20,615
DN2	24,762	26,299	26,352	26,115	25,810	25,932	25,600	25,532	25,036	24,605	24,015	23,432	22,848	22,499	21,978	21,446
DN1	25,931	28,184	28,465	28,310	27,966	27,740	27,235	27,055	26,430	25,845	25,153	24,470	23,806	23,182	22,838	22,277
D	26,864	30,070	30,584	30,506	30,121	29,717	29,033	28,346	27,825	27,085	26,291	25,508	24,764	24,088	23,465	23,107
DS1	23,243	25,956	26,567	26,802	27,037	27,276	27,663	27,509	27,634	27,157	26,495	25,802	25,110	24,467	23,849	23,518
DS2	19,622	21,842	22,550	23,098	23,953	24,834	26,293	26,672	27,443	27,228	26,700	26,096	25,455	24,847	24,232	23,661
DS3	16,001	17,728	18,533	19,394	20,869	22,393	24,923	25,835	27,143	27,299	26,904	26,389	25,800	25,226	24,616	24,054
DS4	12,380	13,614	14,484	15,690	17,785	19,951	23,553	24,998	26,989	27,370	27,108	26,683	26,145	25,605	24,999	24,446
DS5	8,759	9,500	10,461	11,987	14,701	17,509	22,183	24,161	26,834	27,441	27,313	26,977	26,490	25,984	25,383	24,839

This table and later tables created for a commercial installation are invaluable tools for determining where to place individual turbines in order to obtain the maximum amount of energy conversion. Also, there is an added benefit to calculating power densities in this manner. Once the yearly power density is calculated, one can do a simple calculation using turbine efficiency and the area swept by a turbine's blades to calculate the total energy generated in one year. This eliminates the requirement to estimate the capacity factor of the site by estimating which currents are strong enough to generate electricity.

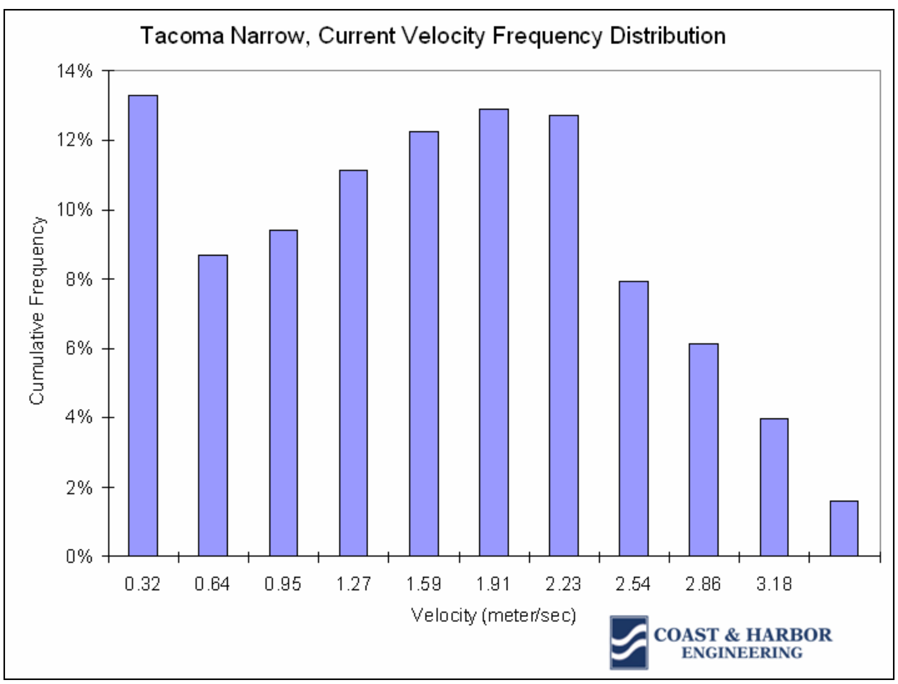
The full channel cross-section power density for Point Evans at Transect D, the transwect with the most power, is shown in Figure 30.

Figure 30: Transect D Power Distribution



A frequency distribution of velocities was calculated for transect location D3 which has the highest power density of all stations. It is shown in Figure 30.

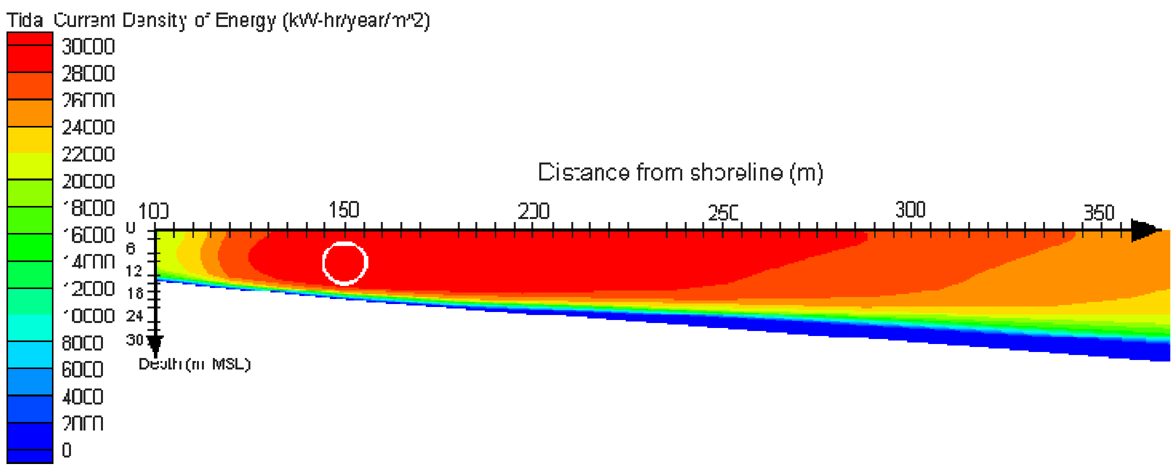
Figure 31: Tacoma Narrows Frequency Distribution



Note that this is the highest-power site in all the Tacoma Narrows. Velocities above 2 m/s happen about 34% of the time. Figure 30 is relevant to tidal turbine performance because most turbines are designed for performance only above 2 m/s, with cut-in speeds of about 1.5 m/s at best. In other words, a turbine at the site with most power will generate any power only about half the time, and rated power less than 20% of the time.

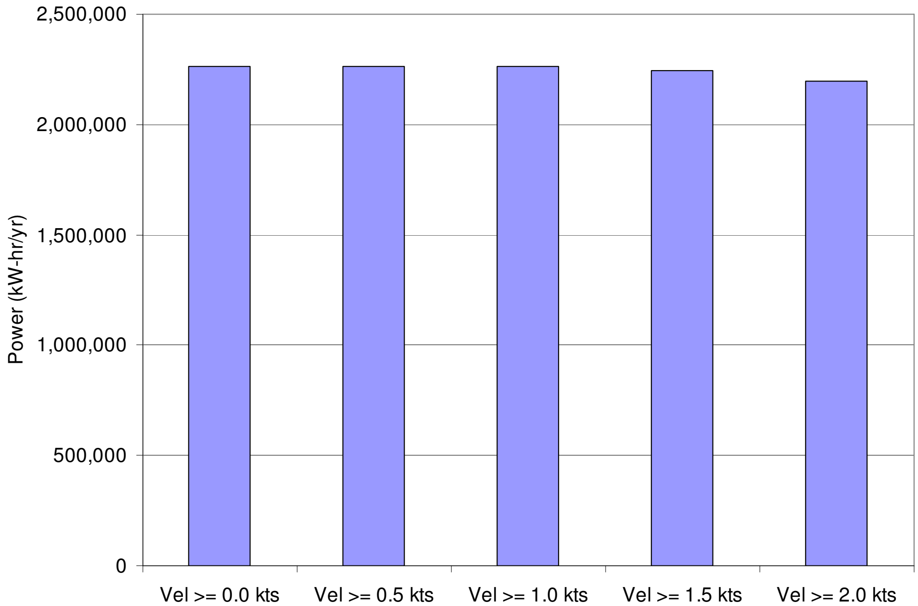
Use of annual power density enables efficient sensitivity analysis to various current velocities. In the sensitivity analysis, an area of 11 meters in diameter in Section D was selected (Figure 32). Yearly energy was computed using all velocities there from the model. The results of sensitivity analysis (Figure 33) show the energy density in Tacoma Narrows only marginally depends on the smaller velocity currents.

Figure 32: Sensitivity analysis location



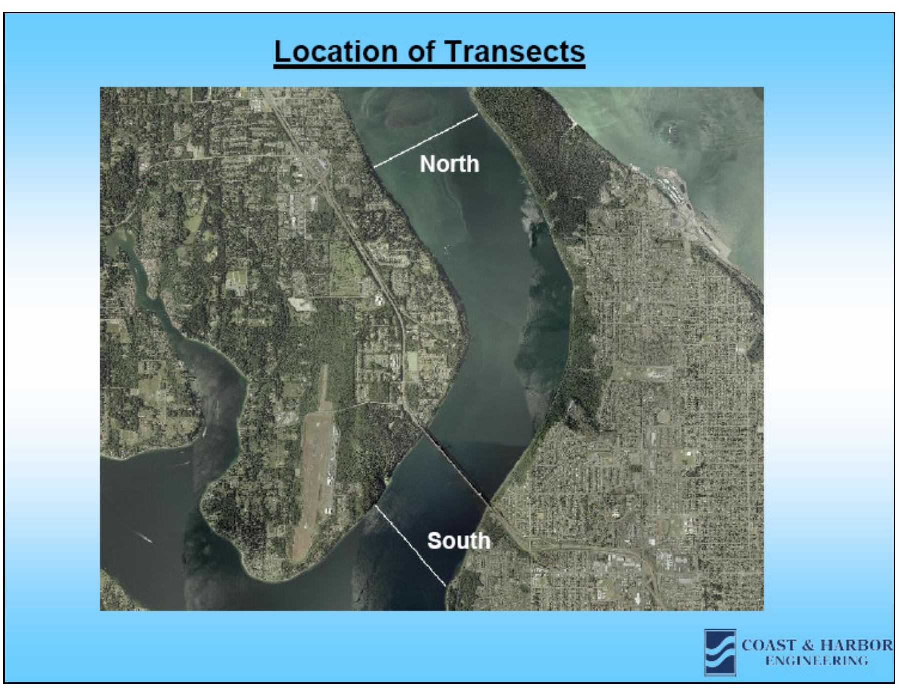
In Figure 33 the first bar represents the total energy excluding no currents, that is Velocities>0. After that, velocities less than 0.5 knots, 1.0 knots, 2.0 knots were excluded sequentially from computations and yearly energy was computed (second bar Vel>0.5 knots, third bar Vel>1.5 knots, forth bar Vel>2.0 knots) respectively. Figure 33 shows that if all the energy from currents < 2 m/s are excluded the total energy is diminished only a small fraction.

Figure 33: Sensitivity analysis results



There is also interest in the power to the far north and south of Point Evans. Two additional transects were calculated as shown in Figure 34.

Figure 34: Additional Transect Locations



The transects were chosen to represent a more linear channel than represented by Point Evans, where turbulence and shear affects power density dramatically. Figure 35 shows the north transect; Figure 36 shows the south transect.

Figure 35: North Transect Power Density

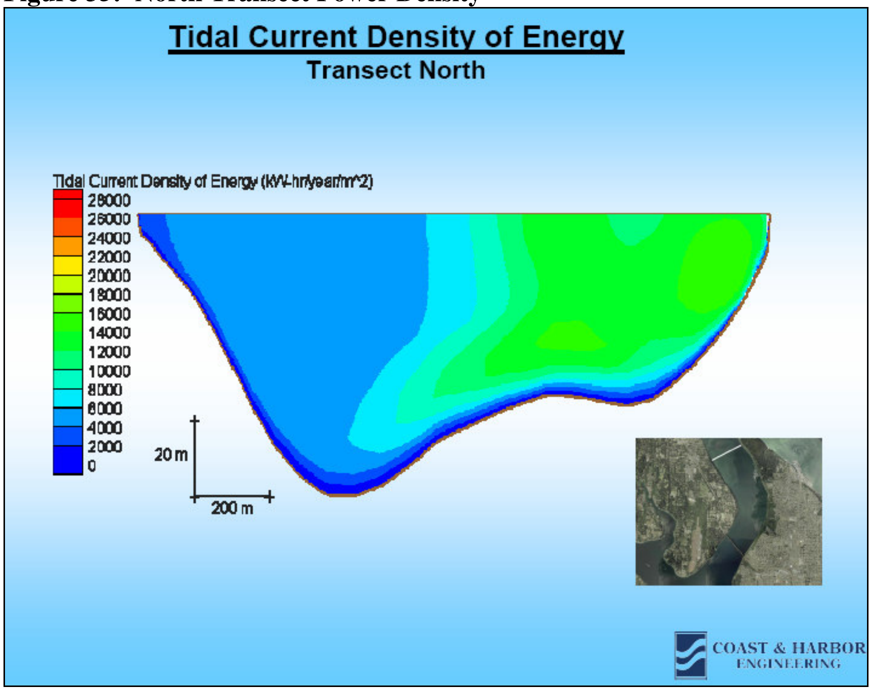
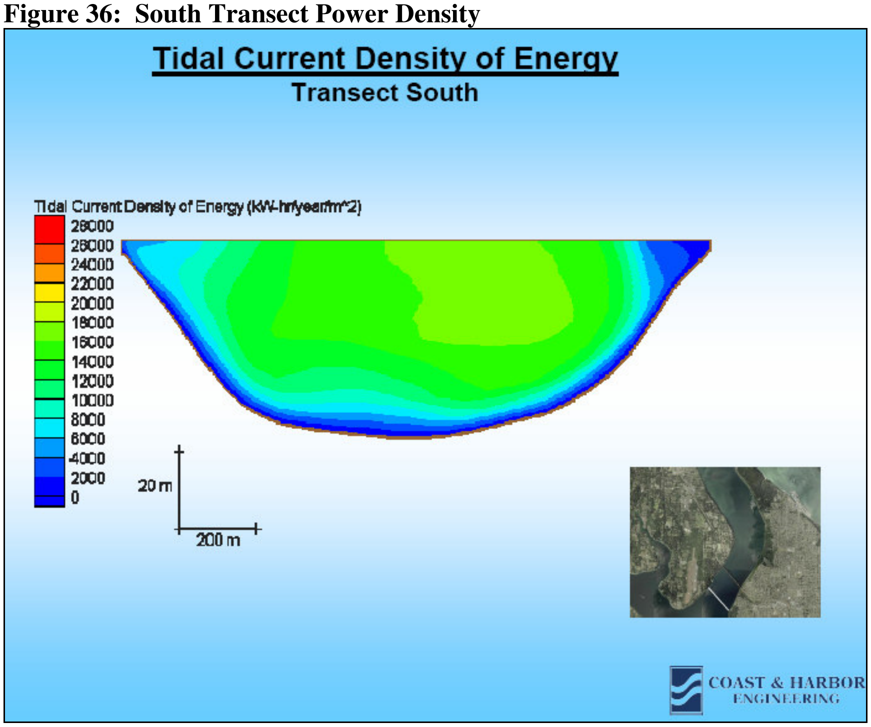


Figure 36: South Transect Power Density



These transects have very interesting implications for Tacoma Power. In the south transect the power densities appear sufficient to support a turbine array of the type proposed by EPRI in its concept analysis. The power density is similar and the channel dimensions are sufficient to support large turbines of 16m as proposed by EPRI and various turbine developers. There appears to be sufficient power and space south of the Tacoma Narrows Bridge to support a tidal power plant of about 10 MW using very simplified assumptions. However, the site is different from Point Evans: The power is found at least 20m above the bottom; turbines at that elevation must be suspended from cables, not attached to tall pilings, thus new engineering for installation is required.

The conclusion of physical oceanography and power modeling is that there is sufficient power in Tacoma Narrows to produce between 10 and 20 MW for at least one site, and maybe for another. If the Pt. Evans array from this study and the EPRI array concept were combined, it might produce about 27 MW using about 300 tidal turbines. Whether such numbers would be allowed is unknown.

The estimates of power potential in this section are simplistic. They do not account for many important factors, such as the effect of upstream turbines on the ones downstream from them, or the cumulative effect of energy extraction, and other factors.

Availability of Current Model

The SELFE current model used for this study is owned by Coast and Harbor Engineering, Inc. (CHE). The output of the model is the product for Tacoma Power as described in this report. CHE is available for further analysis using the model. For example, to calculate the power densities for any transect across the Narrows would take about 8 hours of CHE time at current billing rates – as of October 2007, about $1000 in fees. Now that it already exists, use of this model is highly cost-effective for future studies of Tacoma Narrows. The model can be extended to other areas of Puget Sound but every site requires field data collection to validate the model there.

3.4 Current Model Peer Review Report

Puget Sound currents have been studied for over a century. In the 1980s the University of Washington started the Puget Sound Regional Synthesis Model (PRISM) initiative, with the goal of providing a comprehensive suite of models for the Puget Sound region together with educational and outreach activities; King County, Washington conducted an oceanographic observation program in the north Main Basin of Puget Sound as a part of the study for the siting of the marine outfall for the new BrightWater Treatment Plant, and collaborated with the University for development of a model for the whole Puget Sound; Puget Sound Naval Shipyard in collaboration with SPAWAR in San Diego developed a regional model of the Sinclair – Dyes Inlets and surrounding watersheds; Washington Department of Ecology developed a circulation model of the South Sound region, This activity stimulated formation of a coordinating group, the Puget Sound Marine Environmental Modeling (PSMEM) partnership.

To validate the modeling approach used by Coast and Harbor Engineering Inc. for this study, a review was requested from one of the leaders of the PRISM and PSMEM programs, Dr. Mitsuhiro Kawase, physical oceanographer at the University of Washington. His review is reproduced below in full and unedited.

"A Review of Current Modeling in Tacoma Power Tidal Study"

By Dr. Mitsuhiro Kawase, Oceanography Department, University of Washington

> This review is based on the document "City of Tacoma, Washington – Tacoma Power / Tacoma Narrows Tidal Power Feasibility Study, 2007. Implemented by Puget Sound Tidal Power LLC. Stage Gate 1 Report to Bonneville Power Administration Technology Innovation Office, Sept 2007" as well as an animation file "Tacoma Narrows currents.wmv" distributed by Puget Sound Tidal Power LLC.
>
> In this study, the Semi-implicit Eulerian-Lagrangian Finite Element (SELFE) model from Oregon Graduate Institute is implemented at a very high spatial resolution for simulation of the current in Tacoma Narrows, Washington. The model's outer boundary is placed out in the Pacific Ocean (Figure 5) and the model resolution is telescoped down to the needed resolution in the region of interest. The model is calibrated against current meter measurements made by Evans-Hamilton in July – August 2007. The document does not include some detail of implementation desired for a full review such as vertical resolution and the form of the turbulence closure scheme used; nor does it include graphical comparison of outputs from the calibrated model and observations.
>
> From visual inspection of the model output (Figure 7) as well as from the animation provided, it appears that the model has sufficient horizontal resolution to represent structure of the current within the Narrows channel. The most significant finding is that the region of the highest power density appears in the shallow waters off Point Evans, not in the deepest part of the channel as surmised in a previous study by EPRI.
>
> This reviewer recommends that a full technical report on the modeling work be prepared by Coast and Harbor Engineering including implementation details and model-data comparison. For future study, this reviewer suggests that baroclinic effects of salt stratification should be included in the model. Also the level of turbulence expected in the location of the turbine array in the Narrows channel should be studied. SELFE includes Generic Length Scale turbulence closure model, which would prognostically compute shear-generated turbulent kinetic energy and generic length scale; however, the dynamics of the flow through the Narrows channel is known to include significant non-hydrostatic effects such as a complete overturn of the water column due to centrifugal force during spring tides, which may generate level of turbulence not realizable from shear instabilities. Direct observation of turbulent component of the velocity should be at-

tempted at proposed sites of turbine placement (such as by using a high-frequency ADCP); a high-resolution modeling of the Narrows channel using a fully three-dimensional, non-hydrostatic numerical model may also be necessary.

3.5 SOW for Further Investigation

The main concern for further scope of work in power modeling is the effects of energy extraction on flows and turbine arrays. During this project an extensive review was done of published academic, engineering and developer literature regarding this topic – how much power can you take out of the channel before flows are significantly affected?

There is no clear answer now. The few academically-reviewed analyses published to date show that there is much more advanced modeling needed. Bryden concludes that 10% extraction appears acceptable for simple channels.[9] He also notes that “the limits on sea loch type environments might be less restrictive”. EPRI chose 15% as the limit for energy extraction as a “reasonable assumption” given the various academic studies. The complications of modeling estuaries with complicated channels are already well known; adding tidal turbines and energy extraction to the models complicates them further in as-yet-unknown ways

Dr. Mitsuhiro Kawase, Department of Oceanography, University of Washington, was consulted for strategies to address this challenge.

Conceptual Scope

Research Conference and Workshop:
Modeling the Extraction of Fluid Energy for Generating Renewable Power from Tidal Currents in Estuaries

The Challenge for Ocean Renewable Energy Generation:

> How can we evaluate the extraction of energy in sensitive estuaries by in-stream turbines and their impact on the environment, and how can we use the information to determine the number, siting, and sizing of turbines in estuaries?

The search for renewable energy sources has led to proposals around the world to generate renewable electricity from flowing water currents in oceans and rivers. In Washington State there are sites proposed for tidal energy extraction in the Puget Sound, one of the USA’s largest estuaries (Figure 1). Energy would be generated from submerged in-stream turbines up to 16m diameter with swept area of up to $200m^2$. At optimum efficiency such turbines should significantly reduce the flow through the rotor as energy is extracted.[10] Initial study shows that many large turbines would be needed for megawatt-scale power generation at each site.

[9] Choosing and evaluating sites for tidal current development. I Bryden; G T Melville Proceedings of the Institution of Mechanical Engineers; Dec 2004; 218, 8
[10] http://tech.groups.yahoo.com/group/awea-wind-home/message/7677

Extraction of energy from the currents will have an effect on circulation within the estuary. In Puget Sound this is a significant concern. Parts of the Sound experience low dissolved oxygen (DO) levels in areas of low circulation due to nutrient loading from non-point pollution sources. If circulation is further reduced by energy extraction then DO levels could decrease further, with consequent biological impacts. The number of turbines allowed in the estuary will depend on the effect they have on circulation and environmental conditions.

The turbines interact with each other. In an array the upstream turbines will extract the most energy; as the flow passes through the array the energy will be reduced and the downstream turbines will extract less energy. This affects the economics of the project. However the impact is affected by the channel profile, the spacing of turbines, the current velocities and vectors and other factors. Modeling is needed to determine how turbines could be spaced in channels for best performance.

The turbine sites will also interact with each other. In Puget Sound one large site is proposed at the entrance to the Sound at Admiralty Inlet. Three other sites to the South, at Rich Passage, Agate Passage, and Tacoma Narrows, are alternately upstream and downstream of this site depending on the flood and ebb of the tide. Each site with a turbine array will extract energy, thus affecting the performance of the other site arrays.

It is likely that regulatory agencies will want to determine the total number of turbines that might be allowed in estuaries like Puget Sound, before granting permits to individual projects. This total number will likely be developed in a highly political process in which science can provide facts but public and agency opinion will decide what will be allowed.

We propose to catalyze and facilitate understanding of possibilities and limitations for tidal energy generation in estuaries, and specifically help the Puget Sound region develop a research agenda that will provide the information needed by regulatory agencies.

The proposed **"Research Conference and Workshop: Generating Renewable Energy from Tidal Currents in Estuaries"** at the **University of Washington** will present the state of knowledge about this emerging topic, identify the challenges for moving from theory to implementation, and suggest a research agenda that would provide agencies with the scientific data needed for further dialogue with stakeholders.

From the results of this conference, new research could determine the maximum number of turbines that could be placed in an estuary with acceptable minimum impacts. However, the location of every turbine will be subject to debate from multiple stakeholders and the total number actually allowed will certainly be less than the maximum possible calculated through research. The science is necessary to begin the environmental and social analysis and decision making.

This proposed conference could also begin the process of scoping a generic Programmatic Environmental Impact Statement (PEIS) covering an estuary. This would help

Washington move ahead with its own PEIS for tidal power generation in Puget Sound, if this is desired by the authorities.

We propose an invitational workshop for qualified experts and permit agency representatives to determine how the problems should be attacked and what are the practical research implementation ideas.

Draft Program

Generating Renewable Energy from Tidal Currents in Estuaries
University of Washington, College of Ocean and Fisheries Sciences, Seattle

Format: Invitational expert workshop
Participants: Experts in modeling estuarine circulation and its impacts; agencies.
Duration: Two days
Day One: Morning: Overview presentations from participants
Afternoon: Identification of research challenges and approaches
Day Two: Morning: Discussion of research approaches
Afternoon: Development of possible programs and budgets; discussion with agencies.

Sample Expert Invitational Topics
- actual topics to be determined by conference steering committee

- What will be an acceptable approach to modeling water circulation in estuaries so the physical effects of energy extraction via tidal turbines (on tide elevations, velocities, mixing, salinity, DO, etc) can be estimated.
- Some challenges: Freshwater input from rivers; climate variability incl El Nino; nutrient inputs from existing and future populations.

- How to model insertion of turbines into flows and the effects downstream; how closely can turbines be spaced for maximum performance; cumulative and interactive effects

- What are criteria for determining acceptable changes in circulation. What impacts need to be considered? What to measure – baseline knowledge, what variables are important, what time frame. Acceptability criteria: species, ecosystems, regulations, pollution, recreation etc

- What are existing biological impact modeling tools and how could they be applied?

4 Tidal Turbines

4.1 Objectives and Outcomes

There is a wide variety of designs proposed for tidal and river turbines, but there are very few devices that have actually generated electricity over some period of time. To determine the state of technology and its applicability to the Tacoma Narrows project, a survey was done of all known tidal and river turbine developers. Available and newly provided information was evaluated. A simple scoring system was developed to determine the suitability of the technologies and developers for further consideration by Tacoma Power.

Because there are no tidal turbines available to test in Tacoma Narrows in late 2008 at the earliest, the varieties of technologies were considered in more abstract terms. The objective was to identify combinations of turbine features which, though not available now, might become available in several years when a commercial project might be initiated. The review included installation technologies of which there is also a wide variety.

The outcome of the survey is that there are no tidal turbine developers who can provide a commercial-size field-tested turbine for a pilot project, much less a commercial project. There are two developers who appear to be the best prospects for future partnerships.

Verdant Power Inc. is the leader in demonstrating its tidal turbine technology and it could have demonstration units with field-proven performance available to Tacoma Power in perhaps two years. Verdant Power also appears to have the corporate capacity needed to be a suitable business partner. The company provided extensive information to Tacoma Power in response to the survey they were sent.

Another potential turbine is the OpenHydro device. This is a unique design with only one moving part and clearly not dangerous to fish or marine mammals (except as an obstruction). EPRI reviewed it and referenced a US Navy report that enthused about the design. The turbine is currently being tested at the European Marine Energy Centre. The company did not provide any information to us despite repeated efforts to contact them. Nonetheless the technology is very promising for a variety of reasons.

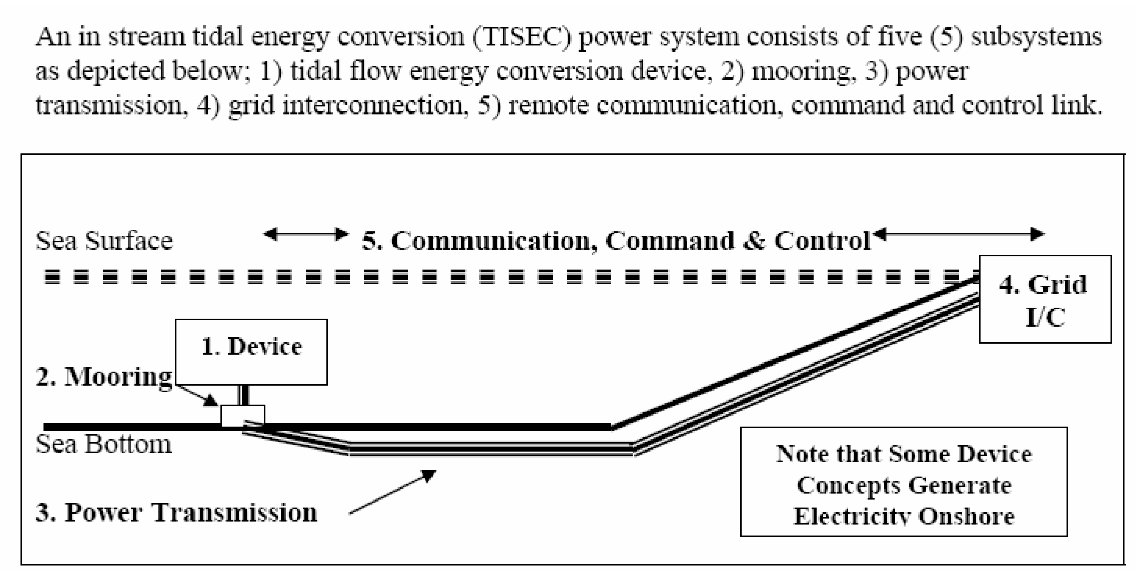
The turbine proposed by EPRI in its study, the MCT SeaGen turbine, was also reviewed extensively. It is not recommended because of its technical complexity and surface-piercing installation structure. No new information for turbine costs, installation construction or O&M were provided by MCT in their survey responses. Therefore the EPRI estimates are the best available and could be used by Tacoma Power for further consideration.

4.2 Tidal Turbine Basics

Turbine technologies and systems are discussed extensively in EPRI TP-004-NA, *Survey and Characterization of Tidal In-Stream Energy Conversion Devices*, and EPRI TP-005-NA, *Methodology for Conceptual Level Design of TISEC Plant*. Please refer to those publications for complete discussion which is summarized here in part.

Turbines consist of several major parts as shown in Figure 37. The Device itself includes the rotor or energy convertor, the generator, the power train which may have a gearbox, the axle and frame, and power electronics. Turbines are categorized in this report by rotor types.

Figure 37: Tidal In-Stream Energy Conversion System Components



The amount of power a turbine can take out of a free-flowing fluid, without any channel wall effects, is limited. For water flowing through an unshrouded turbine, maximum extraction efficiency occurs when the flow speed at the rotor face is reduced by 1/3 relative to the free-stream velocity, which yields an optimal extraction efficiency of 16/27 (=59%), which is the so-called “Lanchester-Betz limit.” EPRI estimates that the total efficiency of an optimized TISEC system would be about 40% at best. Review of reported turbine performance data indicates “water to wire” efficiencies of about 35% at best for unducted turbines.

Turbine power output can thus be estimated from the swept area, power density and efficiency. A 16m-diam. rotor, such as the MCT SeaGen rotor, has a swept area of about 200 m^2. A 2 m/s current has energy of 4 kW/m^2. So the rotor in the current has available power density of 800kW. If it is 30% efficient, it could produce 240kW output.

Turbine efficiency can be increased by the use of a diffuser that creates a zone of low pressure behind the turbine. This increases flow through the turbine. Data from wind and water turbine diffusers or augmentors shows that throat velocity is increased 40%. This increases power density by 300% because power increases as the cube of velocity. The diffuser is an additional structure which adds weight and load to the turbine, therefore the cost-effectiveness of a diffuser depends on the turbine design, size and location. A turbine in a diffuser therefore would have about 3 times the power output of an open turbine.

Turbine efficiency is affected by turbulence and off-axis currents, depending on the design. Open propellers need to yaw or orient into the current so the blade sweep is perpendicular to the flow. If the propeller cannot yaw, it loses efficiency as the swept area is reduced by the change in current vector. In areas of strong shear currents or periodic off-axis currents, a fixed position propeller will lose some efficiency, but ducted propellers are less affected by this and can handle flows up to 20 degrees off axis. In fact, diffuser-type turbines may even have higher efficiency with off axis flows which seem to increase perimeter water velocity in the diffuser and thus increase the pressure drop.

4.3 Turbine Types

4.3.1 Axial-Flow

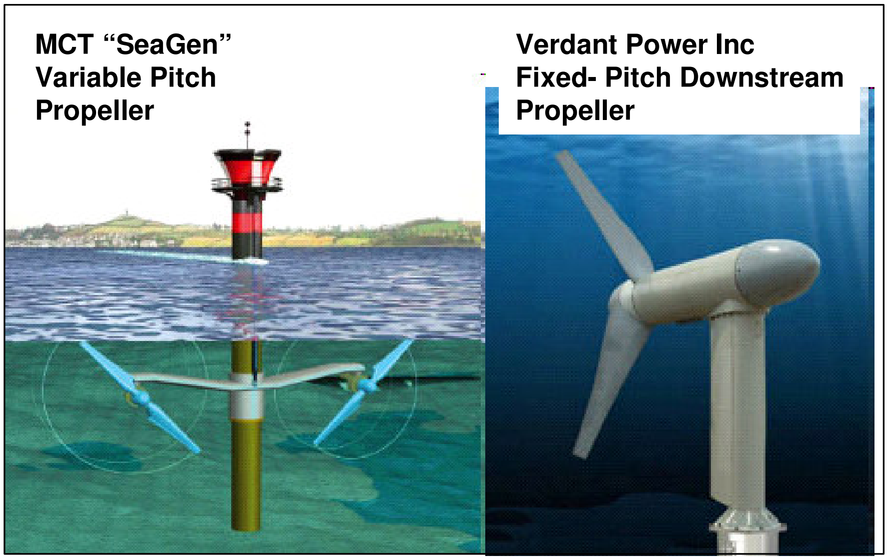
Axial-flow means the flow is parallel to the axis of rotation, for example, in airplane propellers, hydroelectric dam turbines and wind turbines.

Propellers

Many decades of experimentation have settled on open propellers as the most cost-effective means of extracting power from wind. Propeller blades can have controllable pitch, in which the blades can be rotated at their base so the angle of the blade to the wind can be changed. This enables the device to reduce loads in high speed flows and to increase efficiency in low speed flows. It also significantly increases the mechanical complexity of the turbine. Fixed-pitch blades keep the same angle for all flow velocities so they are less efficient over in-flows with a wide speed range, But they are also less complex and expensive to construct. Axial-flow propellers lose efficiency if they cannot yaw into the flow for power extraction.

Most of the tidal turbines proposed are axial propellers. Only one is a controllable-pitch propeller, the MCT SeaGen. The SeaGen is fixed relative to current direction so it cannot orient itself into off-axis currents and therefore could lose efficiency in some circumstance (Figure 38). The Verdant Power turbine is fixed pitch and "downstream" in that the rotor is downstream of the hub and shaft, and it auto-orients into the current.

Figure 38: Turbine Type - Axial-Flow Propellers



A theoretical analysis of fixed versus controllable-pitch turbines was conducted in the UK. The project established the extent to which the loss in energy conversion efficiency of the simpler to construct fixed pitch device is counterbalanced by a reduction in capital and O&M costs and whether the system is technically feasible and sufficiently economic to warrant further development. The conclusion is that “the simple fixed pitch, bi-directional device is competitive on a life cycle cost basis and worthy of further consideration.”[11]

The main disadvantage of this type of turbine is that the open blades could strike objects in the water drifting or swimming through or next to the propellers. There is no evidence to date of this happening but in channels with populations of protected fish or marine mammals the issue can and has been raised.

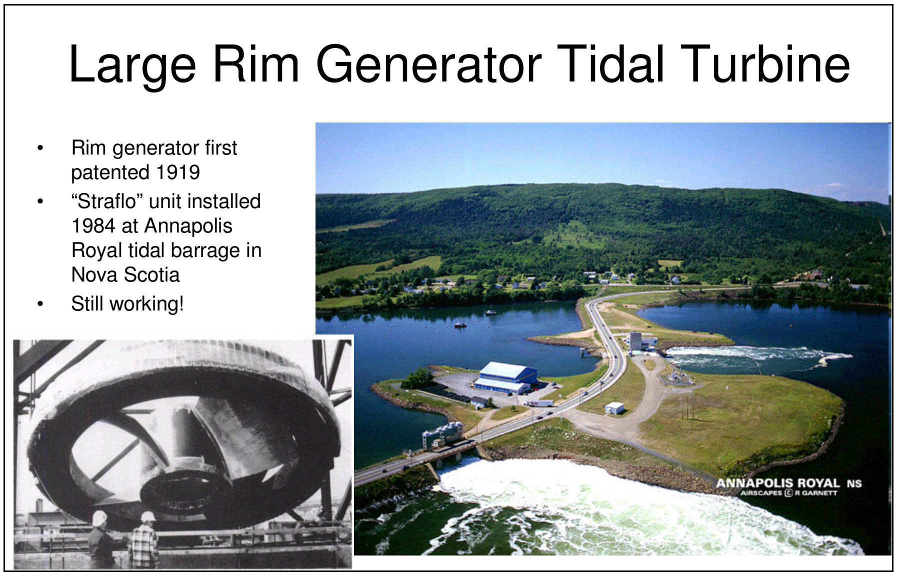
Propellers can be enclosed in ducts which eliminates the problem of blade-tip strikes. A duct that acts as a diffuser can increase the water velocity significantly if designed properly. Ducted propeller turbines are proposed by Lunar Energy Ltd. of UK and Clean Currents Ltd of Canada. The Clean Currents design has been pilot tested at Race Rocks near Victoria, British Columbia. According to the company the tests were successful but no significant data was provided. The list of changes proposed from the test results indicates the low level of current technology development.

Rim Generator Rotor

Another type of axial-flow turbine is the rim generator rotor. The rotor is encased in a circular frame that also holds the magnets. This design is established but uncommon. It has been used as a generator in a Nova Scotia tidal barrage since 1984 (Figure 39).

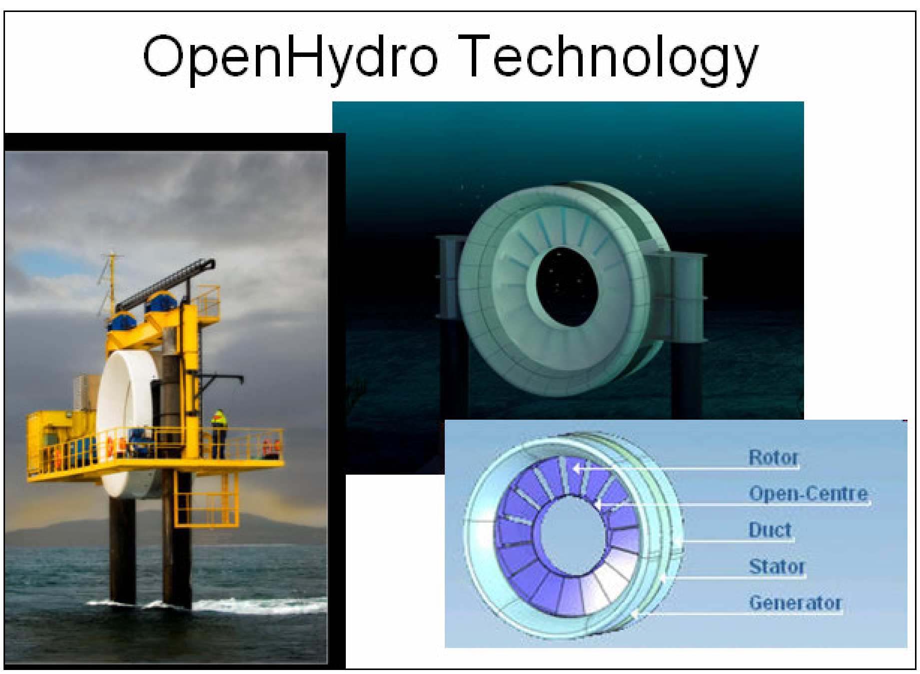
[11] Economic Viability of a Simple Tidal Stream Energy Capture Device. UK Dept of Trade and Industries, Project No. TP/3/ERG/6/1/15527/REP.

Figure 39: Rim Generator in a Tidal Barrage



The OpenHydro Ltd. company of Ireland has developed this idea as a bi-directional in-stream tidal turbine. The ring-shaped rotor is enclosed in a stator to make a generator. A central hole enables fish passage (Figure 40). The generator uses high-density permanent magnets and no gears so the turbine has just one moving part, the rotor. A large proto-type OpenHydro turbine has been sea-tested in late 2007 at the European Marine Energy Centre (EMEC).

Figure 40: Bi-directional instream tidal turbine



Although this propeller does not yaw into the current, it may be less vulnerable to power loss from off-axis currents than open propellers. Evidence from testing the Mo wind turbine diffuser, discussed below, indicates that the duct brings off-axis flows more directly in line with the rotor

4.3.2 Cross-Flow

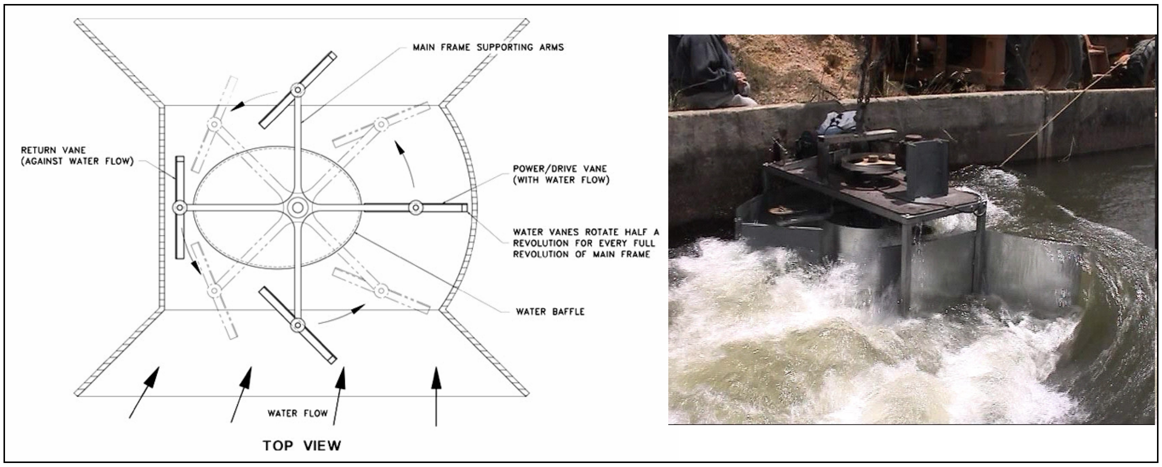
Cross-flow turbines have the current flow across the axis. Waterwheels are the oldest example and are proposed now by Hydro-Gen of France as tidal turbines. Waterwheels are relatively efficient across the range of current speeds and low-cost as the generating equipment is out of the water, but they float on the surface and thus are vulnerable to weather and people and they are obstacles to navigation and aesthetic views. And most of the wheel is not exposed to the flow, so it has less efficiency for its size than a completely submerged cross-flow turbine.

Some cross-flow turbines operate completely submerged in the fluid. They can be installed in either a vertical or horizontal axis position and spin the same direction regardless of the current vector.

Savonius turbines are the oldest of these types. The common cup anemometer for wind measurement is an example. Standard savonius turbines are inefficient because the fluid pushes on the side coming upstream as well as going downstream. The RPM is basically the same as the fluid speed so savonius turbines spin much slower than lift type propeller turbines. However, a novel adaptation discussed below changes that and offers interesting opportunities

The Sundermann Low-Head Water Turbine, invented by F. Sundermann of Victoria, Australia, uses a mechanism to change the angle of the blades coming upstream, turning them sideways so they don't block the water. (Figure 41). The efficiency is thus greatly increased. Since it is a drag turbine, for a fish it is like going through a revolving door and thus low-impact. Several similar designs have been proposed for small wind turbines. This is a concept that deserves further exploration for in-stream applications because of its high efficiency, low impact and relatively simple construction.

Figure 41: Modified High-Efficiency Savonius Turbine



Darius turbines have vertical airfoil lift blades arranged parallel to the axis. The lift from the blades allows them to spin faster than the wind speed, like a propeller. However, the blade speed is slower than a propeller's because the blades do not extend so far from the axis (Figure 41). Darius turbines were tried for wind turbine applications and abandoned because they are prone to destructive vibration at high speeds and also may need a start-up motor. But they are proven as tidal turbine applications. The Kobold turbine developed by the Italian company Ponte de Archimedes is a classic example of a Darius turbine.

Figure 42: Darius-Type Tidal Turbine - the "Kobold"

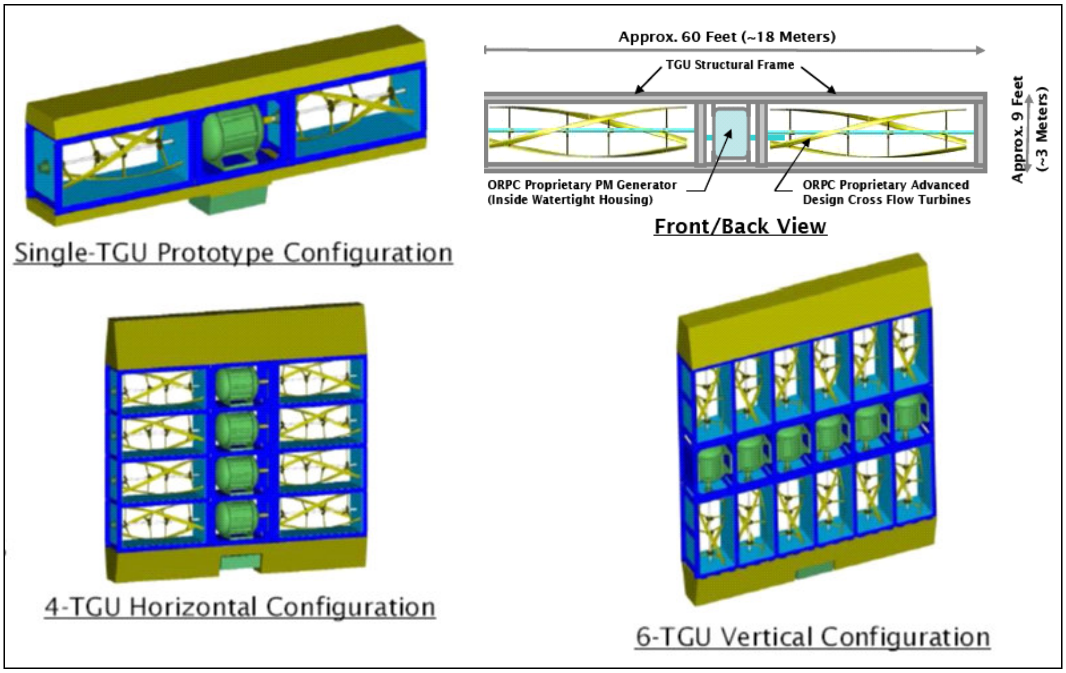
Darius tidal turbine designs have been prototyped by several other developers including Blue Energy Ltd. and Alternative Hydro Solutions Ltd., both of Canada. As true cross-flow turbines, the Darius design can be installed vertically or horizontally, with easily-changed dimensions of length and width, and either suspended from a float or mounted from below on a piling.

Helical "Gorlov" turbines are a variation of the Darius turbine in which the blades are given a helical twist wrapping them slightly around the axle dimension (Figure 43). This dramatically reduces vibration of the blades and may increase efficiency.

Figure 43: Gorlov Helical Turbine - Dr. Gorlov, left - Gorlov turbine double rotor, right

Two tidal turbine developers are using the Gorlov design. Lucid Energy Technologies Inc. holds the original patents and has developed new versions. Ocean Renewable Power Corporation Inc. has developed a variation on the basic Gorlov design and claims a new patent design. It has developed a modular approach to combine multiple rotors into a floating "tidal fence" for large-scale power generation (Figure 44). The Gorlov turbines have been demonstrated in several pilot projects in the USA, Canada and Korea.

Figure 44: Proposed Installation of Gorlov-Style Turbines



4.3.3 Novel Turbines

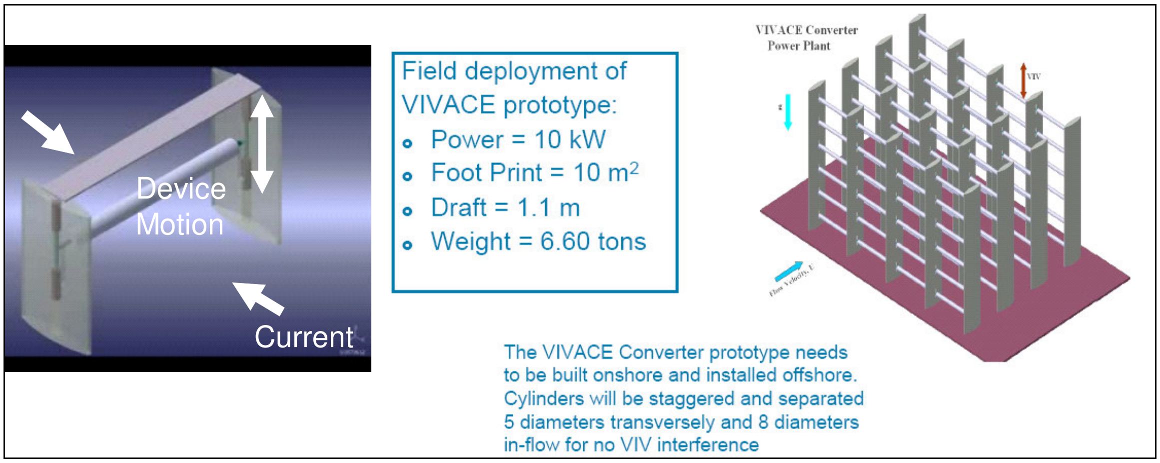
Novel turbines have been proposed for decades by inventive minds. Recently there has been a surge of interest because of high energy costs and climate change concerns. This is reflected in tidal energy but even more in wind energy. The increasing interest in wind energy, which is well proven in contrast to tidal energy, has stimulated many innovations in turbine design. While these are not tested yet in water, there is no reason, in principle, why they would not work as tidal turbines if they are efficient and cost-effective. Figure 45 shows a variety of small wind turbines that already exist. There are clear advantages and disadvantages to the various features of these designs for tidal applications.

Figure 45: Things That Spin in Moving Fluids - a Current Sampling

Given the wide diversity of in-stream fluid energy conversion devices, the utility industry might benefit from an objective study, by an institute of fluid mechanics, of the efficiency of these many turbine designs. A standardized test method would identify which designs generate the most power under various conditions. Manufacturing analysis would determine the gross margins under various volumes of production.

Vortex-Induced Vibration is a unique principal for in-stream energy conversion. It is proposed by the VIVACE company, founded by Dr. Michael Bernitsas at the University of Michigan. The US Department of Energy has provided significant funding for development of this concept. The operating principle is reciprocating motion of a device moved by vortex energy (Figure 46). If a long cylinder is held sideways to a current, it will experience powerful vortex shear cells that create negative pressure on alternating sides. This pulls the cylinder up then down in oscillating motion, which can drive a generator. The optimum cylinder length and diameter for a given current can be calculated from the basic physics, so the technology can be "tuned" for specific sites. However it may not be effective in tidal streams where there is a wide range of current velocities requiring constant "tuning".

Figure 46: Vortex-Induced Vibration Turbine



In conclusion, there are many tidal turbine technologies. None could be considered commercially ready for at least several more years. That may not be a problem considering that permitting agencies will probably take that long to determine how to manage these projects.

There are clear opportunities for marine engineering companies to build and test small versions of these turbines at relatively low cost. Some of the opportunities are discussed in the final section of this report.

4.4 Flow Accelerators and Ducts

The velocity of the fluid current in an open channel can be increased significantly with the use of flow accelerator devices. These surround the rotor and cause a pressure drop behind it, which pulls fluid through the rotor. Jet engine cowlings are a common example.

Note this is not the Venturi effect. That applies only to restriction of the entire channel, such as in a pipe or dam duct. If a small Venturi device is placed in a large open channel, it creates a bow wave upstream and the water flows around it instead of through it. Instead it is a diffuser effect that increases velocity and the diffuser must be downstream from the rotor. A bi-directional diffuser design, such as that proposed by Lunar Energy Ltd. and Clean Currents Ltd., looks like a venturi with its pinched center. But actually each downstream side acts like a diffuser; the upstream portion contributes little to the effect.

4.4.1 Diffusers

Diffuser augmentors for wind turbines were proposed and demonstrated in the 1970s and 1980s. They were further developed in New Zealand in 1998-2003.[12] The latest version, called the “Mo” wind turbine with diffuser, creates 40% increase in throat velocity and at least double the power for the same swept area as a standard windmill propeller of equal diameter (Figure 47). The effect is achieved by inclusion of slots in the circumference of the diffuser which increase flow on the inside walls, thus drawing fluid outwards from then center and decreasing the pressure there. These slots are the apparent “secret” to effective diffuser design.

Figure 47: MO Turbine Diffuser Design

“MO” Turbine Diffuser

achieves shaft velocity augmentation of 1.38 with a diffuser with exit-area-ratio of 2.22 and overall length-to-diameter ratio of 0.35

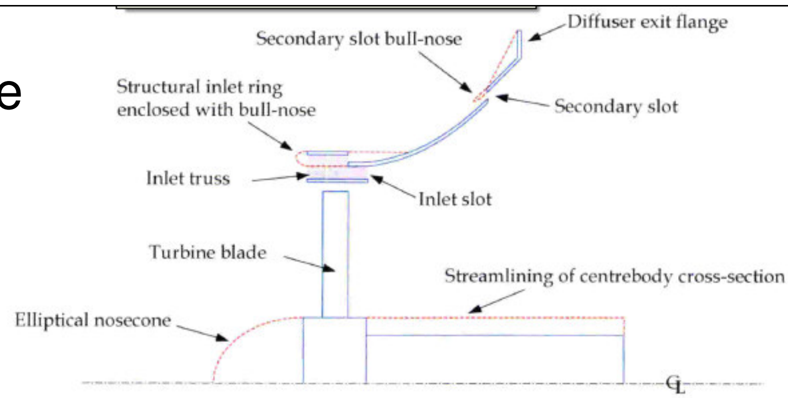
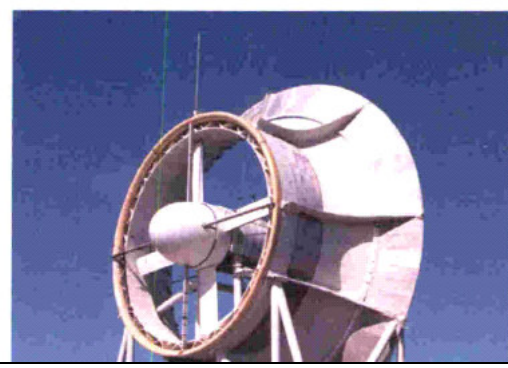


Figure 5.10: Schematic diagram of the modifications made to the Vortec 7 geometry.

The inlet and secondary slots in the rim increase the outward flow behind the rotor and reduce the pressure, thus pulling more flow in and increasing its velocity



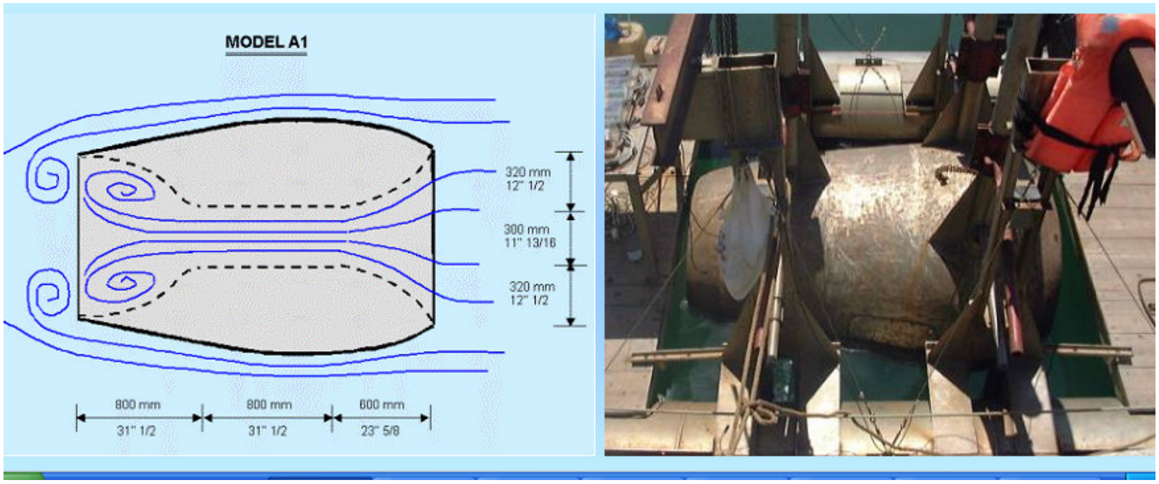
Although the physics and field experiments show that diffusers work, wind turbines have become so large that diffusers are impractical. They must surround the entire rotor, which is already high above the ground, and withstand strong loads. One attempt to commercialize the Mo turbine in New Zealand appears to have failed despite receiving government R&D funds and demonstrating basic performance.

Tidal turbine diffusers have already been developed. The PEERH company of Portugal has patented a design they call the Hydroreactor. It augments velocity about 40%. It is

[12] An investigation on diffuser augmented wind turbine design (2003), Phillips, D.G. University of Auckland Mechanical and Industrial Engineering. http://hdl.handle.net/2292/1940

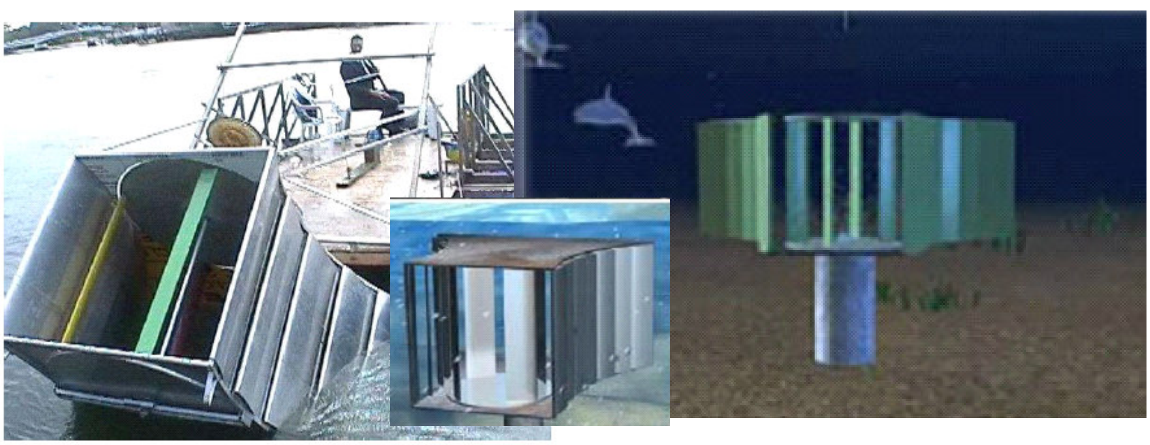
shaped like somewhat like a commercial jet engine nacelle (Figure 48). The acceleration effect is largely from the pressure drop behind the throat of the device. The company is now building a turbine to be installed in the Hydroreactor.

Figure 48: PEERH HydroReactor flow augmentor



Another diffuser concept is proposed by Tidal Energy Pty Ltd., of Gold Coast, Australia. The Davidson-Hill diffuser turbine uses slots in the diffuser sides to create strong interior lateral flows that reduce pressure at the center behind the rotor (Figure 49). The device was studied by Brian Kirke of the Sustainable Energy Centre at the University of South Australia who reports that it produces 300% more power than the same turbine rotor without the diffuser. Of course it is also more expensive than the rotor.

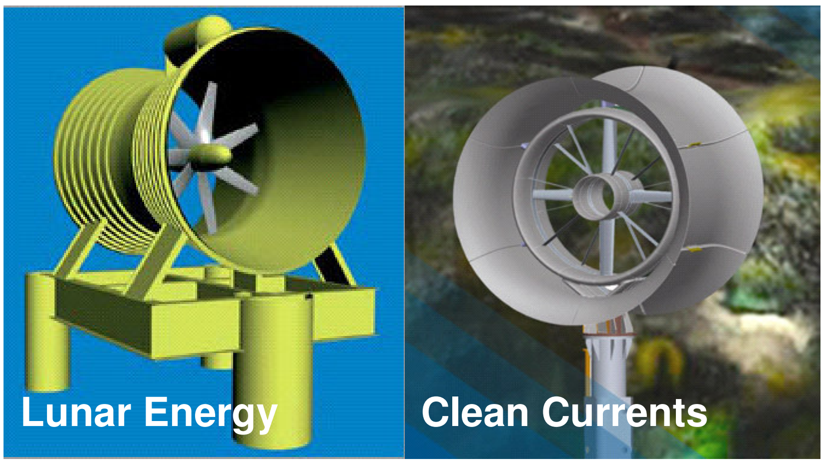
Figure 49: Davidson-Hill Diffuser Turbine



4.4.2 Ducts

Ducted turbines have structures around them that may or may not have augmentation effects. The duct protects the blades and prevents tip strikes (Figure 50). It also helps channel water into the rotor if the flow is up to 20 degrees off the rotor axis. But ducts do not have an augmentation effect because the pinched-waist design prevents smooth flow onto the downstream diffuser face. The full-scale designs proposed by the two leading proponents, Lunar Energy Ltd. and Clean Currents Ltd., are huge, with outside diameters of 24 or more meters / 80 ft and requiring thousands of tons of weight to hold them in place. Figure 50 shows the Lunar Energy design at right and the Clean Currents design at left.

Figure 50: Ducted Turbines Proposed



Ducted turbines would not have blade-tip effects on biota, but anything that enters the duct will be forced through the turbine. If it is debris this could jam the rotor (although the OpenHydro design seems much less prone to this problem). Clean Currents has attempted to address this problem by placing a hole at the center of their rotor and using a rim-drive generator similar to that of OpenHydro. Their device has been tested for six months at the Race Rocks in the Strait of Juan de Fuca near Victoria, British Columbia, Canada. They report no environmental impacts but they did experience problems with drilling the piling (into hard rock) and with the bearings, which were made of Teflon and were abraded by the currents.

Conclusions about ducts for tidal turbines are mixed. They do protect the rotor blades and provide some off-axis flow mitigation. But they do not add significant velocity and thus power output. They add a huge load to the structure and a lot of surface area which increases problems from biofouling. None have been constructed and the extra cost is unlikely to offset the small gains in efficiency.

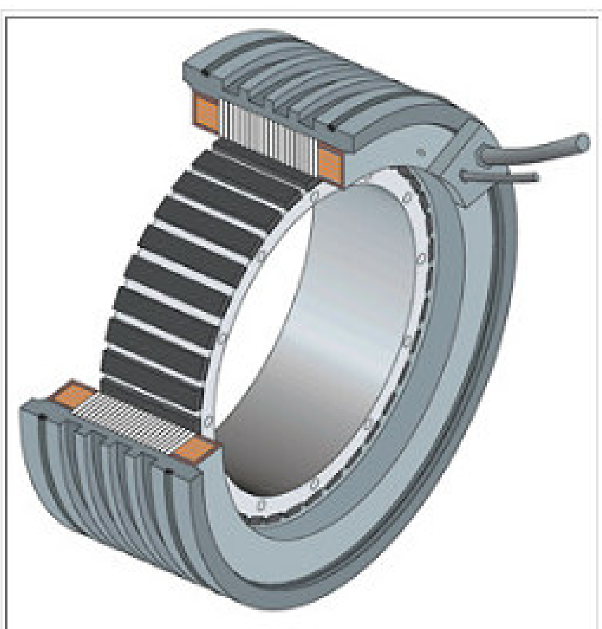
The developers are likely to contest the statement that the power is not augmented. But this is physics; the Venturi effect does not work significantly in an open channel surrounded by free flow. The diffuser effect internally is reduced because the upstream shroud blocks the free current from providing its energy and thus energy differential to the downstream shroud. The MO wind turbine diffuser described earlier works because the free wind hits the upstream surface of the diffuser with full force, not partially blocked by the upstream diffuser shroud.

This problem seems a result of the desire of turbine developers to design for the two-way flow of tidal currents, which at first seems a logical assumption. But the failure of the Venturi principle to significantly increase power in an unrestricted channel seems to have escaped some developers, and the fact that a diffuser must have an un-obstructed up-stream approach also seems unrecognized.

4.5 Turbine Generators

The generators in tidal turbines existing and proposed vary as widely as the rotors. The most traditional approach is to use a standard gearbox speed-increaser and induction generator in a watertight enclosure. This is used by several developers including Verdant Power and MCT, the most advanced developers. Lunar Energy proposes that the rotor drives a hydraulic motor that drives a standard generator. Hydraulic motors are commonly used in underwater operations.

Figure 51: Permanent Magnet Torque Motor / Generator



Torque motors are frameless kit motors consisting of a permanent-magnet rotor and laminated stator.

The trend seems to be towards Permanent-Magnet Generators (PMGs). These use powerful neodymium permanent magnets and are brushless. They begin generating power at the first revolution and smoothly increase power with RPM. The US Department of Energy has investigated PMGs for small wind turbines and concludes they offer superior performance.[13] They have also been investigated for tidal turbines and the performance benefits appear to be transferable to the aquatic application.[14]

The key advantage of PMGs is that they can generate reasonable power at relatively low RPM. In low-RPM ap-

[13] Development of a Direct Drive Permanent Magnet Generator for Small Wind Turbines. U.S. Department of Energy, Grant Number DE-FG36-03GO13139. 2005.
[14] Direct Drive Generator for Renewable Power Conversion from Water Currents. Segergren, E. 2005. Dissertation, Uppsala University.

plications the PMG has wide diameter and many poles. In this configuration the PMG is also produced commercially as a high-torque motor (Figure 51).[15] If the rotor is spun in the stator it produces electricity.

OpenHydro has adapted this concept for its generator design. The OpenHydro rotor has its blades on the inside of the PMG ring. The advantages are: No gearbox; rotor and stator are totally sealed and water-lubricated; very long life / low maintenance; high efficiency at all RPMs. Similar PMGs are being proposed in tidal turbines by Ocean Renewable Power Corp. and Lucid Technologies.

The potential advantage of wide-diameter PMGs are so significant that organizations considering any tidal turbine designs should ask whether they incorporate PMGs and if not, why not.

[15] Torque motors do the trick. Arthur Holzknecht, ETEL Inc. *Machine Design* magazine, 4/2003

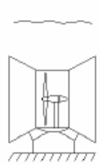
4.6 Turbine Installations

4.6.1 Single Units

Tidal turbines can be installed in a variety of configurations each of which has advantages and disadvantages. The simplest variety is suspended below a barge or float, as proposed by Hyro-Gen and several other developers. The rotor is underwater and the power generation and other equipment is above the water and easily accessible. But such systems face challenges for navigation, surface weather and waves, vandalism, marine life use such as sea lion haul-outs, etc.

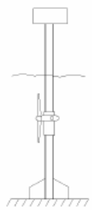
Most invention around tidal turbine installations has focused on submerged or partially-submerged solutions. A fine summary of configurations was conducted by J. Orme[16] and the main results are reproduced here in Figure 52.

Figure 52: Tidal Turbine Installation Options

Telescopic 	• Minor maintenance possible at site – Inspection and access reduces costs if malfunction occurs • Stiff structure – Reduces bearing /structural loads – Rotordynamic stability • Submerged – Not subject to wave action – No visual impact – No presence in splash zone – Low collision risk	• High support cost – High steel cost – Cost increase significantly with depth – Telescopic joint complexity • In raised position tower must withstand wave loadings. • No surface component – Additional navigational markers requ. – Submerged cable connection required • Yawing or blade pitch mechanism required – Additional cost implication • Accurate positioning of installation vessel required – Surface lift
Shroud 	• No yawing mechanism required – Shroud may act to direct flow into rotor • Stiff structure – Reduces bearing /structural loads – Rotordynamic stability • Deep water tolerant – Tower length can be adjusted easily • Submerged – Not subject to wave action – No visual impact – No presence in splash zone – Low collision risk	• Minor maintenance requires complete removal of nacelle to shore • High support cost – High steel cost and weight – Large loads owing to surface area • No surface component – Additional navigational markers requ. – Submerged cable connection required • Vulnerable to marine fouling – Shroud remains in place over lifetime, risk of marine growth / seaweed growth clogging duct and rotor • Accurate positioning of installation vessel required – Submerged lift

16 http://www.swanturbines.co.uk/images/supportstructures.pdf

Figure 52 continued

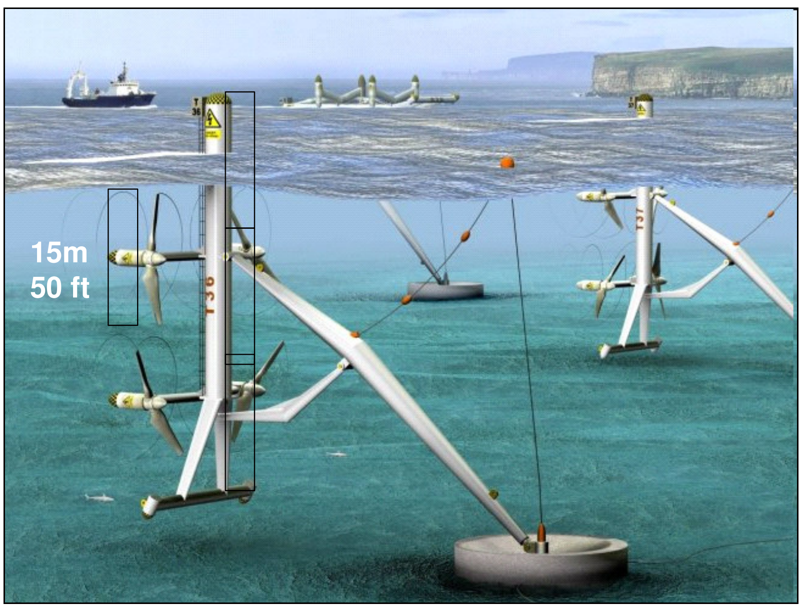
CONCEPT	*SIGNIFICANT ADVANTAGES*	*SIGNIFICANT DISADVANTAGES*
Sheath 	• Electrical components above water – Easy access – Low sealing requirements – Dry connection • Minor maintenance possible at site – Inspection and access reduces costs if malfunction occurs • Stiff structure – Reduces bearing /structural loads – Rotordynamic stability • No additional navigation markers required	• Surface piercing – Visual impact – Shipping collision risk – Corrosion in splash zone – Structure subject to wave action • Tower length and handling – High steel requirement – Cost increases significantly with depth • Accurate positioning of installation vessel required – Surface lift • Hoist mechanism – Exposed to marine growth and corrosion • Yawing or blade pitch mechanism required – Additional cost implication
Anchored 	• Low cost structure – Mainly chain • Deep water tolerant – Chain length can be adjusted easily • Self aligning to flow direction – No yaw mechanism required • No accurate vessel positioning required • Submerged – Not subject to wave action – No visual impact – No presence in splash zone – Low collision risk	• Minor maintenance requires complete removal of nacelle to shore • Very flexible structure – Vulnerable to fatigue loads – Decreased component life • No surface component – Additional navigational markers requ. – Submerged cable connection required • 100% downstream operation – Rotor always passes through wake of structure giving rise to pulses in power and vibration. • Loci of operation – Fewer devices can be installed in area – Higher collision risk
Guyed 	• Low cost structure – Mainly chain • Deep water tolerant – Chain length can be adjusted easily • No accurate vessel positioning required • Submerged – Not subject to wave action – No visual impact – No presence in splash zone – Low collision risk •	• Minor maintenance requires complete removal of nacelle to shore • Flexible structure – Vulnerable to fatigue loads – Decreased component life • No surface component – Additional navigational markers requ. – Submerged cable connection required • Yawing or blade pitch mechanism required – Additional cost implication • Significant underwater work to attach chains
Top Mounted 	• Stiff structure – Reduces bearing /structural loads – Rotordynamic stability • Deep water tolerant – Tower length can be adjusted easily • Submerged – Not subject to wave action – No visual impact – No presence in splash zone – Low collision risk	• Minor maintenance requires complete removal of nacelle to shore • No surface component – Additional navigational markers requ. – Submerged cable connection required • Yawing or blade pitch mechanism required – Additional cost implication • Accurate positioning of installation vessel required – **Submerged lift**

Of these configurations, the Anchored or moored floating system uses the least materials but is subject to vibration from its cables and requires deeper water for its floatation.

Clearly, the type of installation will be dependent on the physical site conditions. As an example, in the deep central channel of Tacoma Narrows the maximum power density is about 15m / 50 ft above the bottom. A shrouded or ducted system would have to be held up that high with attendant huge tipping loads on any piling, or it would need to be anchored and floating. This has never been done or even taken to full engineering as far as we know.

The most sophisticated tidal turbine installation system proposed to date is from Tidal-Stream UK, an entrepreneurial group. They have developed an installation system for large propeller turbines that enables the system to pivot freely into the current and also to release itself and float to the surface for maintenance. There appears to be no major impediment to this concept except its size. Figure 53 illustrates the concept using the size of the ship in the figure for scale. The rotors in the picture are about 50 feet in diameter and the central floatation shaft is about 150 feet tall.

Figure 53: Conceptual Tidal Turbine Deployment System



In conclusion, the variety of tidal turbine installations options is large and the solution depends on the site. If a site is studied and developed to the point where a commercial array seems possible, then the installation question is worth visiting. However, it requires extensive and expensive engineering as well as consultation with all regulatory authorities, who will need to be educated at every step. So further speculation is unwarranted in this report regarding the best installation methods for tidal turbines in general. Applications suitable for the Tacoma Narrows in particular will be discussed below.

4.6.2 Arrays

The type of installation affects the potential spacing of turbines arrays. The installation with the smallest footprint is a piling system with a fixed bi-directional turbine on top of it. The OpenHydro, Darius, or Gorlov turbines would fit this installation. If the turbines rotate into the current they need a larger footprint. If they are floating and moored, the spacing of the cable anchors must be calculated. Large floating systems probably need at least four anchor cables with at least one at each corner so an array of floating systems could be an underwater forest of cables.

The main issues with array engineering are spacing and removability. All indications are that in the USA in general and in Washington State in particular the environmental protection agencies will be concerned about obstructing the path and potentially damaging fish and marine mammals. Therefore pilings would give the maximum density of spacing, but the maximum may not be allowed by the agencies who want to see more room around the devices for animals to get through. If the spacing is set by environmental consideration, then the proper technology is open for discussion.

For this report, the conceptual power generation of an array was developed using 10m turbines mounted on pilings at the maximum density given by assumptions of spacing, for example distance between transects and between turbines along transects. In other words, “we packed them in.” This is done to demonstrate the potential power. Almost certainly such an array would not be allowed as it appears physically impossible for any large marine mammal to transit the array without having an incident with one or more turbines.

4.7 BioFouling and Corrosion

Biofouling has been shown to be a serious concern for turbines installed in Northwest marine waters. The Clean Currents turbine was installed at Race Rocks in the Strait of Juan de Fuca near Victoria, BC. The top of the turbine is about 10m below the surface and daylight illuminates it well. The turbine was tested for six months under water. A week before raising the turbine in April 2007, brown Macroalgae had to be cleaned off the turbine. The divers estimate that within a few weeks it would have reached the surface. This algae can attach to a solid substrate within the top 12 meters of water at Race Rocks.[17] Figure 52 shows a diver on top of the turbine housing surrounded by the algae. Substantial growth was found around other parts of the device and in particular wherever there were seams, bolt-holts or other irregularities that help marine organisms attach themselves.

[17] http://www.racerocks.com/racerock/energy/tidalenergy/april07fouling/fouling.htm

Figure 54: Algae Growing on Clean Currents Turbine

The large macroalgae growth in particular will create significant additional load on the turbine, requiring stronger and more expensive construction. The tendency of organisms to colonize the nooks and crannies would increase maintenance problems. Growth on the turbine rotors themselves decreases their efficiency.

To prevent bio-fouling, the surfaces must be coated with anti-fouling agents. There are a variety of options. According to marine antifouling paint suppliers in Seattle who were interviewed, the maximum lifespan of the most durable commercially available antifouling coatings is ten years. Effective antifouling for five years is warrantied under normal conditions on vessel hulls, but tidal turbines may not be considered "normal" by the manufacturers.

Corrosion is also a concern, particularly in saline environments. Turbine developers are aware of this and use a variety of approaches to combat corrosion concerns. For example the OpenHydro machine is largely composite; the Verdant Power turbines have aluminum blades that don't corrode. However, no devices have sufficient in-water testing time to validate corrosion resistance suitable for commercial deployment.

The effects of biofouling and corrosion will be a concern only if the regular maintenance schedules do not address them. For example, the antifouling coatings could last five years. It is quite likely that the turbines will be removed from the water for mechanical maintenance at least once during the five years, whereupon it would also be cleaned and recoated. So if regular mechanical maintenance is more frequent than the significance thresholds for biofouling and corrosion, these issues may not be of great concern.

4.8 Tidal Turbine Developers

4.8.1 Previous Surveys

Tidal and river turbine developers were surveyed recently by EPRI and by the Government of Canada (using Verdant Power Inc. as consultant). Their full reports are provided separately in digital files with this main report. Figures 55 and 56 below show the summaries of their surveys, which were used to build a new and current survey for Tacoma Power.

Figure 55: EPRI Tidal Turbine Survey 2005

	GCK	Lunar	MCT	Open Hydro	Seapower	SMD Hydro	UEK	Verdant
Device Name	GHT	RTT 2000	SeaGen	OCT	Exim TTPF	TidEL	Underwater Electric Kite	RITE
Type	V-axis Helical Turbine	H-axis Ducted Turbine	H-axis Twin Turbine	H-axis Twin Open center	V-axis Savonius turbine	H-axis Twin Turbine	H-axis Augmented Turbine	H-axis Unducted Turbine
Develop-ment Status	1m dia X 2.5m high test in Merrimack River in Sep 2004.For others see Appendix B	1 to 1.5 m dia (1/20th) scale test in water tank	11m dia 300kW tested at sea (note 1) since May 2003 15kW tested in 1994-5	3m (1/5th) scale testing at sea	Full scale test in Sep 2003	1/10th scale tested	7 prototypes up to 10m in dia – see Appendix H (note 2)	Tested Pakistan 1989, Md and NY in 2002-2003
Next Develop-ment Step	Develop shaft mounted gen unit optimized for GHT	Deploy 1 MW unit in 2006 at EMEC – plan 2MW com'l unit	Deploy SeaGen unit in 2006	Deploy 1.5 MW unit in 2006	Fullscale pilot plant to be commis-sioned in 2005	Fullscale prototype to be deployed at EMEC in 2006	10 MW – 25 unit project in DE - in permitting	Pilot 6-Unit Integrated System in the East River NY
Power Train Type	Direct drive permanent magnet gen connect to GHT shaft	Hydraulic based on modified COTS pump	PlanetaryCOTS Gearbox	Direct rim drive generator	Gearbox	Gearbox	Planetary drive - proprietary	Speed Increaser COTS
Founda-tion/	Suspension or attached to sea floor	Gravity Base	Monopile embedded in sea bed	Gravity base or monopile	Anchors & Chains4-fold	Anchors and chains	Via cable (note 3)	Monopile
Rotor Size	1m dia x 2.5m length	19.5m (3.9 m hub diameter)	2 rotors 18m dia	15m	1m dia X 3 m high – 2 pieces	8m blades on 2.5m dia hubs.	Twin 10ft	5m
Rated Power (kW)	7	2,000	1,548	1,520	44	1,000	400	34
Rated Speed	2.58	3.1 m/s	3..0 m/s with MMSS of 3.5	2.57 m/s	3.0 m/s	2.3 m/s	3 m/s	2.1 m/s
Area (m^2) in $P=0.5\rho AV^3$ equation	2.5	490.8 (cross section of 25m dia duct	5092	313.8	6	537	14.59	19.6
Com'l Price	Yes, turbine only.	Not Com'l yet	Not Com'l yet	Not Com'l yet	Yes, but excluding site specific costs, grid.	Not Com'l yet	Yes	Yes

Verdant Power Inc was contract by Natural Resources Canada to do a similar survey of river turbine technology developers.

Figure 56: Verdant Power River Turbines Survey[18]

New Energy	EnCurrent Hydro Turbine	Cross-axis	Pre-Commercial	no data found	Unducted: 28% Ducted: 55%	no data found	with 5kW Gen: 1.5/ 1.7 duct. 2.0/3.0 unducted	fixed	vert	1.6 for 5kW	1	ducted & unducted	unknown
Blue Energy -Canada	Mid Range Davis Hydro Turbine	Darrieus, cross-axis	Prototype	no data found	no data found	10†/ no data found	1.74/ TBD †	fixed	vert	6.10 †	2	ducted	floating
GCK Technology	Gorlov Helical Turbine	Helical Darrieus Cross-axis	Prototype	~20-38%	TBD	Vert: no min/limit Horiz: ~1.1	0.6 /no limit	fixed	either	1	1 or more sections	unducted	various
Tidal Energy Pty. Ltd.	TBD	Darrieus, cross-axis	Prototype	no data found	no data found	no data found	no data found	fixed	vert	1.2 to 2.4	2	ducted	unknown
Bosch Aerospace	CycloTurbine	Cycloidal Turbine	Laboratory	39.6% † (ducted)	29.3% † (ducted)	TBD	TBD	varies	horiz	TBD	1	ducted & unducted	various
Water Power Industry	WPI Turbine	Darrieus cross-axis	Prototype	49.9	No data found	TBD	TBD	varies	vert	TBD	1	unducted	unknown
PADDLEWHEEL TURBINES													
Eco Hydro Energy Ltd	Floating Power Station	Paddlewheel	Prototype	no data found	no data found	no data found	no data found	flexing paddles	horiz	Various dia's; e.g. 240MW has 18m wheel + 14m blades	1 or 2 in prototype Modules link	unducted	boat-like float
Encore Clean Energy Inc	River Bank Turbine	Turntable Paddlewheel	Laboratory	no data found	no data found	no data found	no data found	NA, folding bucket	vert	no data found	multiple	ducted	floating platform
HYDRAULICALLY TAPPED DUCT SYSTEMS													
Hydro Venturi	Rochester Venturi	duct with hydraulic tap & air turbine	Prototype	no data found	20% †	<1m/100	1.5 /30.5	NA	NA	NA	1 or more RV's can share 1 airturbine	ducted	weighted base?
FANBELTS													
Atlantis Energy	Aquanator	Fan-belt	Prototype	no data found	no data found	~10/ no data found	1.0/no data found	fixed	NA	9m tall x 57m wide	1 belt	unducted	no data found
FLUTTERVANES													
Arnold Cooper Hydropower Systems	Oscillating Cascade Power System	Fluttervane	Laboratory	58-61% †	TBD	1.5/15 †	1.5/4.5 †	flutters	vert	7.3 x 3.0 x 0.9	N/A	N/A	no data found

Both reports and all data are available for download.

To summarize both reports, there a few companies with turbines that actually work but none have achieved any notable success at demonstrating them, including the small inexpensive devices. Very little data can be found about actual performance and the developers in general are not helpful with demonstrable facts about their technology. Only Verdant Power appears to have a technology suitable for Tacoma Power for a realistic pilot project within the next two years.

[18] Technology Evaluation of Existing and Emerging Technologies: Water Current Turbines for River Applications. Natural Resources Canada Contract # NRCan-06-01071, 2006. Prepared by Verdant Power Canada

4.8.2 Survey of Developers

From April to October 2007 during this project, all available sources were used to identify active tidal turbine developers, even those with just well-conceived concepts and some business activity. We did not survey patents filed of which include many tidal turbine concepts.

In evaluating the information, we found many incorrect claims and distortions. Most tidal turbine developers discuss their devices in terms of rated output, which is the maximum tidal speed for which they design. But as our own analysis of tidal power density shows, the average power is about a third of the rated or claimed power. We also found developers claiming electric power that is simply impossible, more than the available power density of the flowing water current. However, some developers do provide relatively good information.

To evaluate the developers, several criteria were used to score them.

Power Generation
Have they actually generated any electric power at all? 0 = none, 1 = a little, 2 = pilot project, 3 = steady power with good performance

Technology Status
How advanced is the technology? 0 = on the drawing board, 1 = prototype made, 2 = prototype field tested, 3 = working devices

Longevity
How long have they been in business and proving themselves? 1 = just started, 2 = several years, 3 = 5+ years and serious business activity, including the main business partner (in a few cases the tidal turbine business is a small side business of a bigger company)

Readiness
How soon are they going to be ready to show Tacoma Power their technology? 0 = no chance soon; 1 = within 5 years; 2 = within 2-3 years maybe; 3 = within 2-3 years probably. Note that there a several small turbine makers that could have a device in the water soon, but only at 2-3 kW power.

Data Quality
How good is the information we could get from them? 0 = no data, just claims and pictures; 1 = some data; 2 = detailed data from them; 3 = detailed data from verifiable studies

Business Credibility
What kind of potential business partner for Tacoma Power do they appear to be? 0 = not credible and no real business capacity; 1 = in business but no experience; 2 = in business and functioning but low capacity; 3 = fully functional as a business partner.

Each developer was rated and the scores summed and sorted. Results are presented below:

Figure 57: Ranking of Tidal Turbine Developers

Tidal and River Energy Generation Technology Developers
Current as of 10/15/07
Author Burton Hamner

	Name	Power Gen	Tech Status	Longevity	Readiness	Data Qual	Biz Cred	Sum
1	Underwater Electric Kite	3	3	3	2	3	2	16
2	Verdant Power	3	3	3	2	2	3	16
3	Marine Current Turbines	3	3	3	1	3	3	16
4	Clean Current	3	3	3	2	2	2	15
5	Marlec	1	3	3	3	1	3	14
6	Open Hydro	3	2	3	2	1	3	14
7	Ponte di Archimede	3	3	3	1	3	1	14
8	SMD Hydrovision	2	2	3	2	2	3	14
9	Thropton Energy Services	1	3	3	3	2	2	14
10	Lucid Technologies	3	2	1	2	2	3	13
11	New Energy	2	2	2	1	2	2	11
12	Blue Energy	2	2	3	1	1	2	11
13	Water Power Industries AS	2	2	1	2	2	1	10
14	Hammerfest Strøm AS	2	2	3	0	0	3	10
15	Alternative Hydro Solutions Ltd.	1	2	2	1	1	1	8
16	Oceanflow Energy	1	2	1	1	1	1	7
17	HydroVenturi	2	1	3	0	0	1	7
18	Vortex Hydro Energy LLC	1	1	1	0	2	1	6
19	Ocean Renewable Power Compa	0	1	1	0	1	1	4
20	Swan Turbines	0	1	1	0	0	2	4
21	Teamwork Technology bv	1	1	1	0	0	1	4
22	Hydro-Gen	1	1	1	0	0	1	4
23	Lunar Energy	0	1	2	0	0	1	4
24	Tidal Stream	0	1	1	0	1	1	4
25	Atlantis Resources Corporation P	0	1	1	0	0	1	3
26	Crest Energy	0	1	1	0	0	1	3
27	Natural Currents Energy Services	0	1	1	0	0	1	3
28	Neo-Aerodynamic Ltd Company	0	1	1	0	0	1	3
29	Tidal Generation Limited	0	0	1	0	0	1	2

The grading of developers is qualitative and informal and should not be used for decisions without further outside consideration. Given the number of developers it takes some time to sift through their information.

Some of the results need clarification. At No. 5, Marlec makes a small propeller turbine for river applications that it claims has operating success and is available for sale now. But it is small and not appropriate scale for Tacoma Power. The same is true for Thropton Energy Services.

4.8.3 Survey Tool

From the list of developers that steadily evolved over the project, a mailing list was compiled which we distributed a survey tool. The survey has detailed questions about many aspects of turbines. The survey is included in the CDROM for this report. All the developers on the list were sent the survey repeatedly. A number of them requested it, but did not return it. Some of those who received the survey felt the information was obtained from an industry source was too complex and time-consuming to warrant their respondance, despite their interest in general.[19]

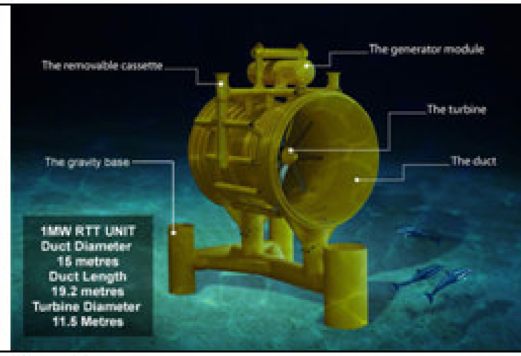
4.8.4 Survey Responses

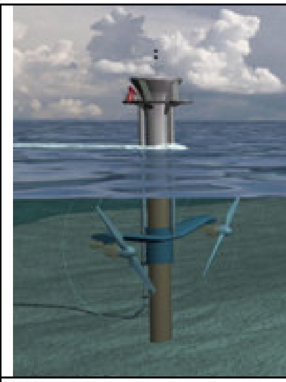
The information that was obtained from developers was compiled and evaluated by Prof. Bruce Adee from University of Washington. The evaluations follow for:

1. Clean Current
2. Water Power Industries AS
3. Lunar Energy
4. Marine Current Turbines
5. Ocean Renewable Power Company
6. OpenHydro
7. Tidal SMD Hydrovision
8. UEK

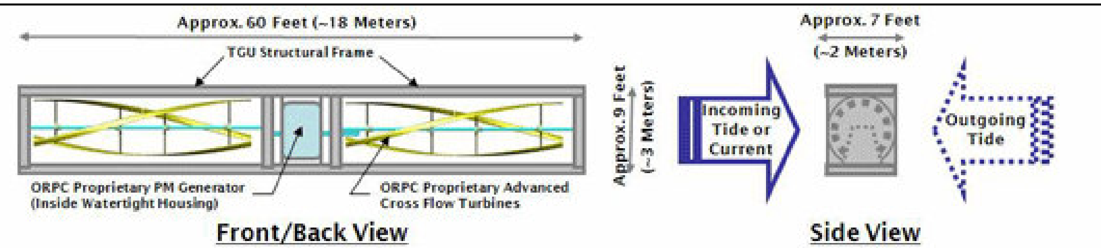
[19] Personal Communication, Sean O'Neil, Executive Director, Ocean Renewable Energy Coalition, Sept 2007.

Clean Current Power Systems Inc.		
Characteristics	**Advantages**	**Disadvantages**
• Classification: Axial Flow • Rotation: Rotating • Mounting: Gravity base or Pile Mounted • Ducted rotor • Directionality: Fixed Direction, bidirectional flow through rotor • Size: Duct max diameter = 24 m Throat diameter = 17-19 m • Four Blades – fixed pitch • Generator: permanent magnet • Status of Development CFD Analysis Model testing in 2002 and 2004 Prototype installed at Race Rocks in BC for 8 months then removed • Rated Power: 1.2 MW @ 3.0 m/s, 13.5 RPM • Current speed required to begin power generation: unknown • Environment Review ongoing at Race Rocks site Low frequency noise Biodegradable lubricants used	• Simple generator • Field tested locally • Gravity base less of a hazard • Potential Canadian government support	• Potential bio-fouling of duct • Installation problems with gravity base • Heavy weight is difficult to handle • Available data quality and completeness

Lunar Energy United Kingdom	 	
Characteristics	**Advantages**	**Disadvantages**
• Classification: Axial Flow • Rotation: Rotating • Mounting: Gravity base • Ducted • Directionality: Fixed direction, bidirectional flow through rotor • Size: Duct size 15 m diameter (prototype) • Number & Type of Blades (controllable pitch) • Rotor drives a hydraulic pump, generator is driven by hydraulic power • Status of Development Model testing and CFD analysis Prototype tests planned for 2008 Rated Power: 1 MW @ unknown current speed • 1 m/s current speed required to begin power generation	• Hydraulic system replaces gearbox • Gravity base is less of a hazard • Gravity base allows removal	• Potential bio-fouling of duct • Installation problems with gravity base • Heavy weight is difficult to handle • Gravity base requires rotor to be near bottom • Available data is limited • No prototype tested

Marine Current Turbines Seagen Current Turbine		
Characteristics	**Advantages**	**Disadvantages**
• Classification: Axial Flow • Rotation: Rotating • Mounting: Pile Mounted • Open rotor • Directionality: Bidirectional • Size: Rotor 16 m Diameter • Two Controllable Pitch Blades with two units mounted on a cross beam • Induction Generator with speed increasing gearbox • Status of Development Seagen under construction Seaflow model installed May 2003 Preparing for testing Seagen • Rated Power: 1.2 MW @ 2.3 m/s, 10-20 RPM efficiency: 48% • Estimated Power @ 2 m/s 0.79 MW @ 48% efficiency • Starting current speed 0.7 m/s required to start	• Above water maintenance • Wider range of higher efficiency using controllable pitch rotor blades • Large size • Stability and strength of structure	• Hazard from surface piercing device • More complexity • Too large for Tacoma project • Less efficiency in off-axis inflows • Limited in-water operation time • Mounting reduces efficiency on alternate tides • Removal of structure (piling)

Ocean Renewable Power Company



Characteristics	Advantages	Disadvantages
• Classification: Cross Flow • Rotation: Rotating • Mounting: Moored • Partially ducted by structure • Directionality: Mooring permits orientation to current direction; Units are bidirectional • Size: Unit includes two rotors and one generator (18 m by 3 m by 2 m) • Three fixed blades per rotor • Permanent Magnet Generator • Status of Development Design complete Reduced-scale unit to be tested in 2007 • Rated Power: 250 kW @ 3.09 m/s per unit • Current speed required to begin power generation not specified	• Oriented vertically reduces loss due to inflow current direction	• Oriented horizontally allows loss due to current inflow direction • Higher rotation speed could harm fish and mammals • Potential bio-fouling of side structure • Side structure may reduce efficiency when inflow current direction is from side

OpenHydro Ireland		
Characteristics	**Advantages**	**Disadvantages**
• Classification: Axial flow open center • Rotation: Rotating • Mounting: Gravity base • Ducted • Directionality: Bidirectional • Size: 15 m rotor diameter • Numerous blades in ring with open center • Permanent magnet generator • Status of Development Models have been tested Prototype installed at EMEC Orkney Is. test facility Commercial contract with Nova Scotia Power • Rated Power: 0.75 MW @ 2.57 m/s efficiency: 48.8% • Estimated Power @ 2 m/s 354 KW @ 48.8% efficiency • Starting Current Speed 0.7 m/s required to start	• Ducting protects fish from blade edges • Open center allows small fish to swim through	• Bottom mounting difficult in Tacoma

SMD Hydrovision **United Kingdom**		
Characteristics	Advantages	Disadvantages
• Classification: Axial Flow • Rotation: Rotating • Mounting: Moored, may attach to gravity base • Open • Directionality: Orients to current direction • Size: Dual rotor 18 m diameter • Two Blades fixed pitch • Gearbox driving AC generator • Status of Development Model testing of 1/10 scale model Prototype awaiting testing at EMEC • Rated Power: 1 MW @ 2.57 m/s, 0 – 20 RPM efficiency 23% • Estimated power @ 2 m/s 480 kW @ 23% efficiency	• Mooring system flexibility • Designed to return to surface for removal	• Lack of prototype testing • Uncertain rated power data • Gearbox increases mechanical complexity • Uncertain behavior in cross currents

The Underwater Electric Kite Company		
Characteristics	**Advantages**	**Disadvantages**
• Classification: Axial Flow • Rotation: Rotating • Mounting: Moored or Pile Mounted • Ducted • Directionality: Orients to current • Size: Individual Element from 1 to 7 m diameter, twin or single units • 5 Blades – fixed pitch • Generator: Alternator with speed increaser • Status of Development Prototype tested in several locations Commercial contracts in place • Rated Power: 66.8 kW @ 2.56 m/s, 39.3 RPM efficiency: 106% for single 3.05 m diameter unit • Estimated Power @ 2.0 m/s 31.7 KW @ 106% efficiency • Current speed required to begin power generation 0.5 m/s	• Duct increases power extracted • Orients to inflow current direction • Mooring easier to remove	• Misgivings about data provided • Lack of experience in mooring an array of devices • Gearbox increases mechanical complexity • Potential bio-fouling of duct • Large-scale ducts are expensive and difficult to produce

Verdant Power		
Characteristics	**Advantages**	**Disadvantages**
• Classification: Axial Flow • Rotation: Rotating • Mounting: Pile Mounted • Open rotor • Directionality: Free to rotate into current direction • Size: Rotor diameter = 5 m • Three Blades, fixed pitch • Induction Generator • Status of Development Conceptual Design and Model testing Prototype array installed in New York Not commercially available yet • Rated Power: 35 kW @2.1 m/s, 35-40 RPM efficiency: 38% • Estimated Power @ 2.0 M/s 30.3 kW @ 38% efficiency • Starting Current Speed 1 m/s required to start	• Extensive in-water experience • Rotates to orient itself to current • Fixed pitch rotor blades less complex • Below surface piling less of a hazard • Extensive in-water data available	• Rotor blades bent during trials • Problems with bolts holding units to piling • Fixed pitch rotor less efficient at current speed off design speed • Rotor always downstream of structure • Removal of structure (piling)

Water Power Industries AS **Norway**		
Characteristics	**Advantages**	**Disadvantages**
• Classification: Cross Flow • Rotation: Rotating about vertical axis • Mounting: Surface or submerged Mooring, Bottom Mounted • Open • Directionality: Works equally with current from any direction • Size: Scaled to fit requirements • 3 Vertical Blades, computer controlled pitch (or orientation) • Generator Type not available • Status of Development Model Testing 2 m diameter by 1.5 m vertical dimension (4th model)	• Simple construction • High torque and low speed • More friendly to fish	• Less efficient • Unbalanced loading during operation • Only testing of rotor has been accomplished

4.8.5 Conclusions

Turbine Developers
The tidal turbine review confirmed that there are only two companies that have technologies of the scale appropriate for commercial power and capable of demonstration in Tacoma Narrows in two years: Verdant Power and OpenHydro. The Verdant Power turbines, in their next generation of development, appear suitable. They have been demonstrated in the East River of New York in 2007, though not without problems that can be solved by better engineering and construction. The free-swinging downstream fixed-pitch rotor is attractive for its simplicity. The company has the capability to manage significant demonstration projects. The open rotor design is a concern for places with endangered species because it raises speculation about blade strikes (which have not been seen so far).

Verdant Power has proposed installing its turbines using a floating system instead of pilings which have proven to be quite expensive. But they have not proposed a well-engineered solution yet. The Verdant Power device is similar to the TidEL turbine, which is also a downstream fixed-pitch rotor. TidEL proposes their turbine to use two counter-rotating rotors and a system to anchor the floating turbine so it orients to the current. This would work just as well with the Verdant Power devices, it appears. Therefore the Verdant Power turbines could be tested in a variety of installation configurations.

The OpenHydro turbine is technically the most attractive design because of its great simplicity, having only one moving part. It appears incapable of hurting fish or marine mammals except by physically obstructing their passage. But the bi-directional design sacrifices some efficiency, and it is not able to orient to changing current vectors in the fixed installation proposed by the company. The OpenHydro company is now demonstrating their system at the European Marine Energy Center and has signed a development agreement with Nova Scotia Power. The company appears suitable for a business partnership with Tacoma Power based on the limited information we can obtain. OpenHydro has not proposed a floating installation system and the proposed gravity base or piling systems have not been fully engineered yet.

Neither company is ready now to demonstrate their technology in Washington. If discussions are initiated with them in early 2008 we expect they could be ready to demonstrate their systems in 2009.

Several other technologies show promise, but are not as suitable. As discussed earlier, there are some small river turbines already available but they are surface mounted and too small for Tacoma Power's needs and would not be suitable for pilot projects.

The MCT SeaGen turbine was used by EPRI to model power output of a tidal array in Tacoma Narrows and elsewhere. MCT has received funding to build the SeaGen but as of November 2007 they have not yet installed it in its test site. It will be at least one to three years before the system testing demonstrates conclusive results. The SeaGen device is mechanically very complex, including controllable-pitch blades and an elevator mechanism for the entire double-rotor turbine. This raises concern about increased maintenance and failures. The surface-piercing design is almost certainly not suitable for Tacoma Narrows for navigation and aesthetic reasons. The piling must be very large because it supports two rotors. The efficiency is likely to be decreased somewhat by the shear currents in the Narrows. Although the company appears competent and well organized, it is entirely focused on its UK applications and markets now.

The UEK turbine is advanced, but the company itself lacks substance as a potential business partner and in twenty years has been unable to take its technology past short demonstration projects.

The Clean Current turbine has been demonstrated in a field test in this region. Performance data from the test was not provided to us. Problems were experienced with drilling the installation piling and with the bearings for the rotor, according to news reports. The company proposes that its full size turbine will have a 15m rotor and a 24m duct which makes it physically the largest turbine proposed, bBut the duct does not increase efficiency and massively increases the structural components and cost.

Turbine Performance
Most of the reported turbine performance is estimated, not field proven. And most of the estimates are for current velocities of 3 m/s or more. As noted in Figure X above, these velocities happen in Tacoma Narrows less than 3% of the time. The efficiencies of the turbines measured against current velocity are less than 40% and we feel 30% efficiency is a more realistic estimate of output.

The simple power calculations discussed earlier therefore appear relevant and applicable to the turbines reviewed. The largest rotors proposed have a diameter of 16m and swept area of about 200 m2. A current with velocity of 2 m/s has power density of 4 kW/m2. Therefore power available to a 16m rotor is about 800 kW. With efficiency of 30%, the turbine would produce about 240 kW/hr when the current is 2 m/s or more. This matches the information provided by or derived from Verdant Power, MCT and other developers' data.

But in Tacoma Narrows at the most power site the current exceeds 2 m/s only about 35% of the time. So 240 kW x 0.35 = 84 kW. To make 10 MW average power about 120 16m turbines would be needed. In comparison, EPRI used the MCT design to estimate an array of 128 16m turbines to produce about 16 MW. The different analyses therefore reach similar conclusions regarding the magnitude of power production potential.

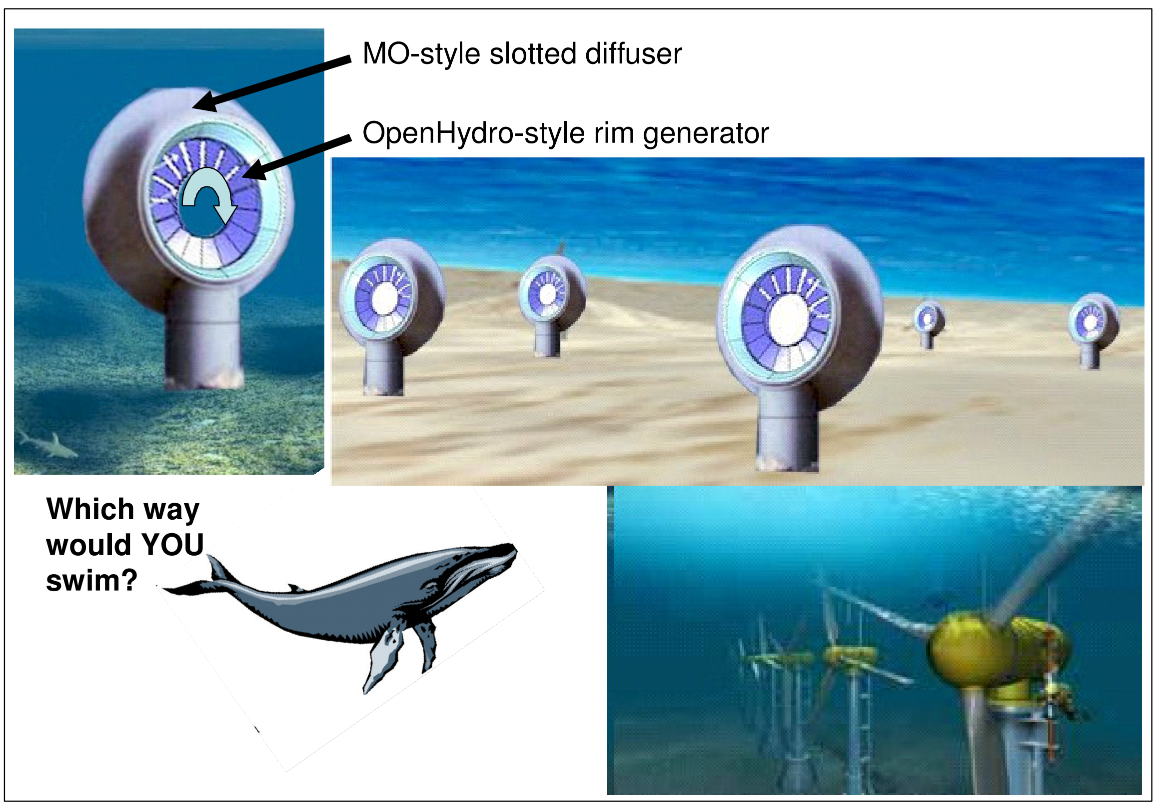
Technology Choices
The best turbine design for Tacoma Narrows appears to be the OpenHydro design. It is dramatically simpler and probably much less expensive to construct, its maintenance will be less, it does not have open blades that could strike animals and objects, and it is scal-

able. It can be installed on a piling or gravity base. The technology could be ready for licensing and local construction in two or three years.

The output of all the turbines can be augmented by the use of a diffuser. This will effectively double the power for the swept area of the turbine including the diffuser. The OpenHydro turbine being tested now has a diameter of about 20 ft. A diffuser around it would have diameter of about 30 ft. This is the maximum size that would fit into the high power areas at Point Evans in Tacoma Narrows. The turbine would need to be mounted on a piling with a swivel base so it can orient to the current since the diffuser is uni-directional. In general an OpenHydro turbine with a diffuser might be expected to make about 1.5 times the power of an open-blade turbine of the same total swept area. It would do so with many fewer moving parts and lower construction costs, but higher installation costs due to higher structural loads.

Figure 58 below illustrates the concept. The unit swings into the current because the diffuser acts like a kite tail. In an array there would be no open blades creating hazards and animals such as whales might be able to navigate through unharmed, and for sure not being struck by the blades. Considering the additional advantages of lower cost and higher performance, this is a possibility worth serious consideration by any tidal power site developer.

Figure 58: OpenHydro Ring Turbine Combined with "MO" Diffuser



4.9 Turbine Design Observations from the Verdant Power RITE Project

BioSonics began working with Verdant Power in 2004 by monitoring for fish and diving birds in the Merrimack River as Verdant tested a Gorlov Helical Turbine. They continued working for Verdant Power as it has implemented the Roosevelt Island Tidal Energy project and observed issues with turbine design and installation. The section below is an excerpt, lightly edited, from their report regarding the design of a hydroacoustic monitoring system for Tacoma Narrows.

"[In the Verdant Power RITE project} FERC established strategies to mitigate project risk. The last step was to remove or shut down a project. This strategy may provide an unacceptable risk to many investors. A more suitable strategy is to be able to shut a turbine off when an unacceptable risk is detected or predicted. The acoustic system can provide the detection capability and the communication message to the turbine. We suggest that turbine manufacturers strongly consider designing in either a braking system or an ability to vary the propeller pitch to neutral, thus stopping blade rotation. If this capability exists in the turbine, then regulators will likely have a higher comfort level with a hydrokinetic project that can be stopped by biologically triggered events. Additionally, turbine vendors need to build in a communication protocol so that commands can be sent to and received from the turbine.

The high flows typical of a hydrokinetic project imply significant risk to both turbines and blades. We suggest that turbine vendors consider designing their systems so that blades can be replaced relatively easily, perhaps by scuba divers. We observed at the RITE project in New York City that when turbine blades were broken by impact with objects or by high flows, the project then incurred the high cost of removing the entire turbine from the floor of the river. Turbine designers should evaluate the possibility of a design in which the propeller hub could be quickly removed by a scuba diver and hoisted to the surface. It could be argued that blade damage is inevitable: the strategy of easy propeller removal would substantially reduce maintenance costs.

Many turbine designs utilize a rigid mount attached to the bottom substrate, such as a monopile. Using the same logic as we did for damaged propellers, the project would benefit by designing turbines that could easily be removed from their mount and from their electronic cable. In such a scenario, a diver would approach the defective unit at slack tide, attach a floatation collar to it, disconnect the turbine from its mount and cable, and inflate the floatation collar to lift the unit to the surface where it could be towed or lifted to a work area.

When turbines are installed and are left over long periods of time, it is almost inevitable that a drifting rope will foul them. Several manufacturers produce a cutting tool for boat propellers that will cut fouled lines off automatically. We suggest that such technologies be evaluated to determine if they could be scaled up to provide protection for hydrokinetic turbines."

4.10 SOW for Further Investigation

Tacoma Power is not a turbine developer and it should rely on the market and competition among the existing and future developers to demonstrate which turbine technology works the best. But some topics could be worth further investigation.

Tidal turbines are large and they should be constructed locally if possible. The cost of constructing an OpenHydro type turbine in Washington should be relatively easy to estimate based on available information, since all the components are well known and the structure is composite, within the scale at which Washington state composite fabricators now work for the aerospace industry. The cost of rim-drive generators of the proposed size can be obtained from local sources. This device would benefit in particular from economies of scale and high volume production because the parts are large, simple and few in number per unit. If a decision is made to engineer a commercial project this should be done early to determine turbine unit costs and volume discounts.

The issue of installation technology is in fact a local issue and Tacoma Power may have to make choices about it. There is significant political and environmental concern about any turbines being installed "permanently" in Puget Sound. Piling installations in particular appear relatively permanent although they can in fact be removed with modern equipment.

Anchored or moored systems are much less permanent and potentially much less expensive than pilings. The TidEL turbine from SMD Hydrovision is proposed with an anchored system which could satisfy stakeholder expectations for "removability". But such moored systems have not been engineered before and significant analysis would be necessary to determine how to best manage it. Fortunately, capital costs would be relatively low. Some investigation of mooring designs suitable for the Narrows would be appropriate.

5 Construction and Operations Costs

5.1 Turbine Installation Cost Analysis

A pre-feasibility level engineering analysis was conducted for a tidal turbine support structure. The monopile turbine support system was selected for further evaluation on a prototype and array installation. A concrete or steel gravity base foundation system was evaluated but eliminated. Due to factors relating to foundation stability, size, and constructability, this type of structure is more suited to shallower depth applications (shallower than 30 to 40 ft depth). A floating support structure was also evaluated but determined to be feasible for only a prototype installation.

Design Criteria

The following criteria were developed in coordination with the project team and based on the best available current information:

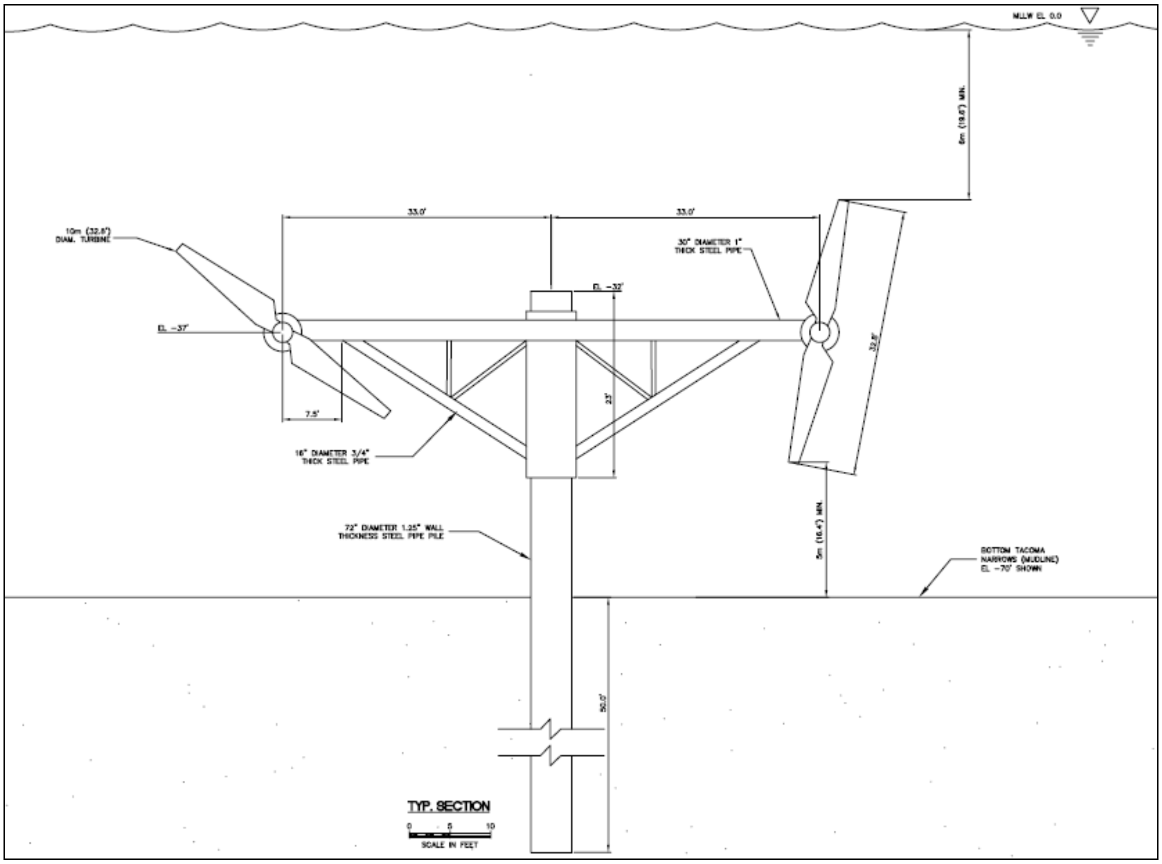
- Two 32.2 ft (10 meter) diameter Turbines (Seagen or Verdant Power type axial Turbine)
- The Turbine Support Structure (monopile system) shall be a completely submerged installation. Maintenance will require underwater recovery.
- Minimum 5 meter clearance from seabed to bottom of turbine blade
- Minimum 5 meter submergence from lowest tide elevation to top of turbine blade
- Minimum depth for operation = El -70 ft MLLW based on design criteria
- Turbine lateral spacing on each monopile structure shall be a minimum of ½ turbine diameter or 5 meters
- Soil conditions were estimated from existing data sources such as Washington State Department of Transportation Tacoma Narrows Bridge construction: Medium loose sand and gravel overlaying hard, dense glacial till.
- A turbine reaction load of 25 kips (applied at the center of the turbine) for the 10m diameter turbine was selected based on CHE computations and limited information provided by an axial turbine manufacturer.
- Support structure current loads (computed using Morrison's Equation) to be added to turbine reaction load.
- Deflection shall be limited to prevent permanent soil deformation during peak lateral loading of monopile structure (estimated to be less than L/360).
- Deflection criteria for operation of turbine not available and assumed to not be critical.
- Resonance frequency of turbine support structure relative to turbine will not be reached. Information on natural frequency of the turbine was not available at the present time.
- Design life for turbine support structure assumed to be 25 years.
- Turbine array located outside of navigation channel; therefore, no deep-draft vessel considerations.

Engineering Analysis
An engineering analysis was conducted using the criteria developed and the best available existing information. A turbine support structure composed of steel pipe would be the preferred structure construction method in order to minimize structure cross-section and turbulence. Tidal current loading is the primary force exerted on the turbine and turbine support structure at the proposed depths and structure configuration. Wind and wave loading will not be a factor for the submerged monopile support structure installation.

Current loads were estimated using the Morrison Equation for round tubular structures. Three-dimensional structural analyses were carried out applying all types of loading (torques, current, and deadloads). A uniform pipe pile thickness was used for quantity and cost estimating at this level of conceptual design. Variable thickness pipe could be utilized to minimize steel material costs once a more detailed pile analysis is conducted.

Conceptual level details of the turbine support structure are shown in Figure 59. A seabed elevation of -70 ft MLLW was selected for the evaluation of the structure, since it represented a typical average depth for the location of the proposed array. Based on loading analysis, the monopile size was estimated to be a 6 ft diameter with 1.25" wall thickness. Concrete pipe fill could be considered to further stiffen the monopile to reduce deflection and modify natural frequency of the pile support system. Pile size is for the depths listed on the concept drawing. Other locations within the area may be deeper, and therefore require a larger pile size. Fatigue loading was considered during the selection of the monopile pile size based on an estimated 25-year design life.

Figure 59: Diagram of Double-Rotor Monopile Turbine Installation



Since the structural elements are constructed from steel, attention to corrosion protection during the design will be critical to their ability to meet the design life. All steel components would need to be coated with an appropriate marine grade coating system to minimize the effects of long-term corrosion. Additional measures including implementation of a cathodic protection system and/or providing a corrosion allowance in the form of additional wall thickness will be analyzed during subsequent design phases.

Cost Estimate

The construction cost for building a single monopile structural support system is estimated to be **$700,000**. This is an order-of-magnitude/conceptual level estimate in 2007 dollars and the base amount includes furnishing the structural steel elements, pile driving, setting the turbine in place, and related field installation work. This amount does not include mobilization, contingencies, turbine cost, data collection (geotechnical, bathymetry survey, etc.), permitting, maintenance, or other design and construction engineering costs. It is estimated that increasing the production/installation level total to more than 100 turbine support systems may reduce the total construction cost by up to approximately 30 percent.

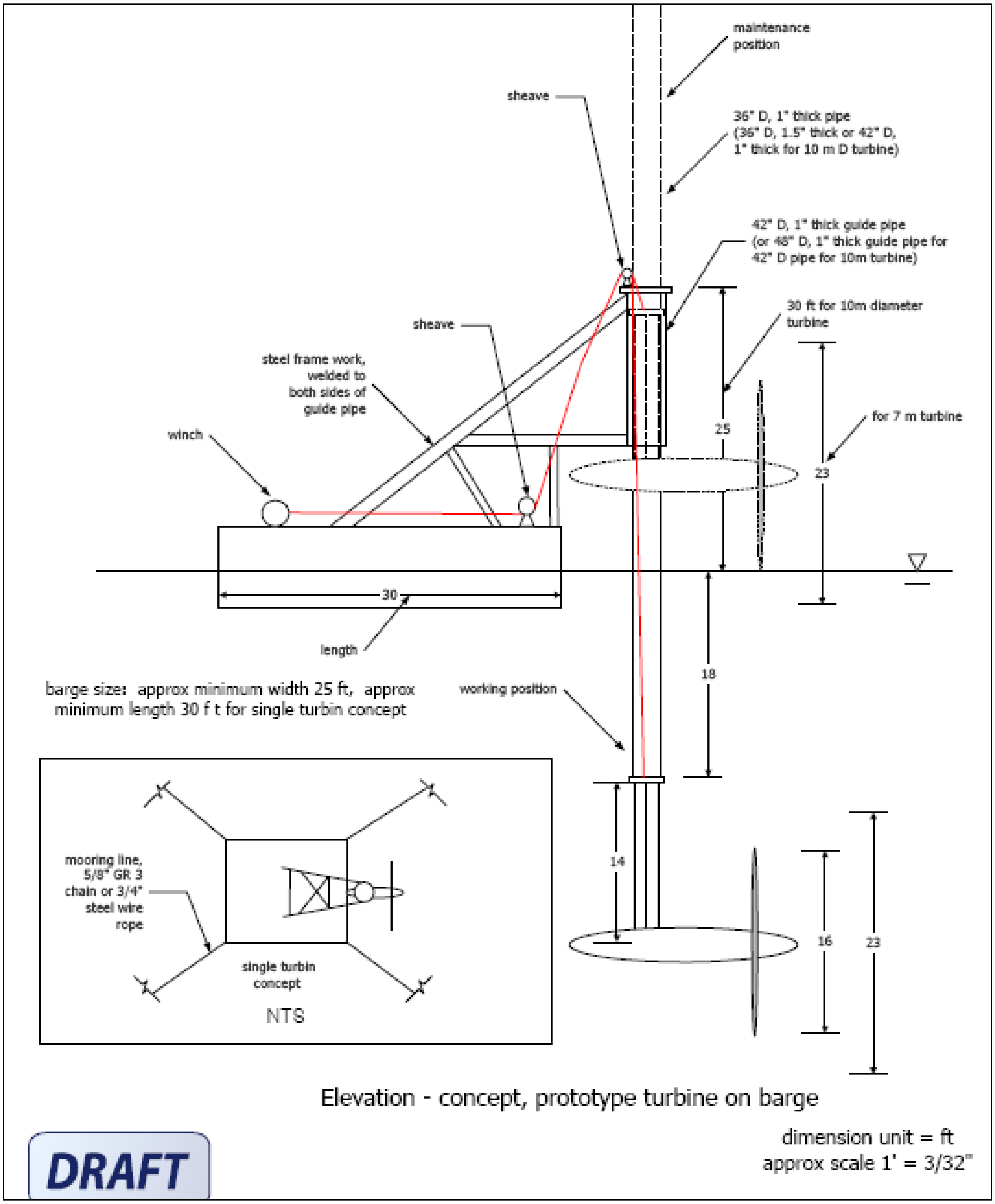
Next Phase Engineering Analysis
Recommendations for the next phase of engineering analysis/design were developed and consist of the following:

1. More detailed geotechnical data collection at the proposed turbine installation site. Marine borings will be required to verify soil types, strengths, densities, and depths in order to further evaluate pile embedment requirements and to assess pile drivability.
2. Obtain more detailed information from Turbine manufacturer for hydrodynamic loads on the turbine. Minimal information was available from manufacturer at the present time.
3. Develop criteria on pile top deflection relative to turbine operations.
4. Conduct a lateral pile analysis using updated loading and soils information. Lateral pile analysis could utilize L-PILE or similar computational software to conduct a sensitivity analysis on pile size versus embedment depth for updated soil conditions.
5. Update structural design of the monopile support structure and evaluate variable thickness pipe.
6. Evaluate natural frequency of turbine support structure relative to turbine to ensure resonance frequency does not occur.
7. Consideration for fatigue loading once pile and turbine size is optimized.
8. Perform a risk assessment and/or value engineering to review, refine, and validate the preferred alternative and associated costs and contingencies.

5.2 Design for Short-Term Turbine Demonstrations / Pilot Project

EPRI proposed a pilot project using a single MCT SeaGen turbine on a monopole foundation. Cost was estimated at about $4 million, of which about $3 million is installation and related systems. The high cost of piling installations is an obstacle to funding tidal turbine demonstrations and pilot projects. An alternative concept was developed that uses an elevator on a barge to lower turbines into the current and retrieve them. Coast and Harbor Engineering conducted a basic engineering analysis of the elevator structure needed for this concept, shown in Figure 60. The elevator is a long tube that slides in a sleeve tube held firmly by a brace structure. A winch with cable attached to the bottom of the long tube lowers and raises the tube through the sleeve. The turbine would be installed on the barge at the dock. The barge would then be towed and moored into place using a four-point anchor system as shown. The turbine would be lowered into place and operated.

Figure 60: Turbine Test Platform Design



The system allows testing a variety of turbines. Since no one turbine developer is likely to build this system just to demonstrate their device, the system should be funded and managed by a third party.

This concept allows viable testing. Test results would include:

- Power generation by the turbine over tidal cycles.
- Maintenance requirements of the turbine itself, depending on the duration of the test.
- Reaction of aquatic life to the turbine, which could include releasing hatchery salmon directly upstream of the turbine during full operation.
- Reduction of flow directly behind the turbine after energy is extracted, and the measurable wake distance and physical parameters.
- Biofouling and corrosion of the turbine.

The test results would be extrapolated to the operation of the turbine when it is installed on a monopole foundation.

Benefits of this approach include:

- The barges are already available and the elevator structure is relatively simple and inexpensive to manufacture at local shipyards.
- The test platform itself can be the system officially permitted by environmental and other agencies, with the condition that different turbines can be installed on the same test platform with proper notification and planning.
- Turbine developers do not need to obtain permits and need only deliver their device to the site and help with its testing.
- No power transmission cable to shore is needed to measure turbine power; it can be measured on the barge and then dumped as heat into the water using a resistance load of iron. The volume of water flowing through the Narrows is so large, and the water so cold, that even 100 kW of energy injected into the Narrows as heat should have no measurable effect (however this needs to be confirmed through further analysis). An alternative is to transmit the power to a shore substation and to float the cable with highly visible buoys. This avoids the high cost of burying the cable in the sea bottom, but it does create a possible navigation concern.

The cost of the system shown above was not calculated because the extra engineering expense is premature at this time. However, it will be much cheaper than the pilot project construction cost of $4M calculated by EPRI, perhaps less than half that amount. Once built, the floating barge has higher operating costs than a submerged piling installation because the barge may require a crewman on board at all times for navigation safety. This would need to be negotiated with relevant authorities. This would be a funding concern more for tests of long duration to collect maintenance or biofouling data and less for short tests of power generation, fish impacts or wake analysis.

5.3 Site Survey

Before any construction could begin at the Point Evans site or elsewhere in Tacoma Narrows, the bottom must be surveyed for accurate bathymetry, hazards such as shipwrecks or cables, and geotechnical data.

Williamson and Associates Inc. (WAI) was asked to develop a scope of work and budget for conducting a survey of Tacoma Narrows. Because the cost for mobilization and demobilization and data analysis is relatively independent of the size of the area surveyed, the scope covers the whole Narrows.

The area will be from just north of Point Defiance south to Gibson Point on the SE corner of Fox Island, a distance of seven nautical miles. The survey will extend from shore to shore, an average distance of 1500 meters.

Three separate types of survey will be done, some of which can be conducted concurrently: bathymetry, sidescan sonar imagery and geotechnical, or sub-bottom.

Principal equipment will be:

- Bathymetry — Reson 8101 or similar
- Sidescan Sonar — Klein 3000 or similar to detect targets one foot on largest dimension
- Sub-bottom — 3.5 kHz and Uniboom sub-bottom profilers. Uniboom has a peak frequency of about one kHz. These two systems should find depth to bedrock as long as it is within about 80 meters of the seabed.
- Nav System — We will use a Trimble RTK system which has a base and a mobile station which will provide us with an accurate elevation (tide).
- Vessel — Kvichak 56 foot Defender catamaran

All primary survey lines will be run up-current/down-current. Some tie lines will be run during periods of minimal current. The bathymetry and sonar surveys will be run on nine primary lines spaced about 200m apart at a speed of 3.5 – 4.5 kts. The SBP survey will be run on 18 primary lines. Any gaps in coverage will be filled in as necessary.

Deliverables will be a bathymetry chart, a mosaic of the entire area with sub-mosaics of selected sites and a "depth to bedrock" map of the area.

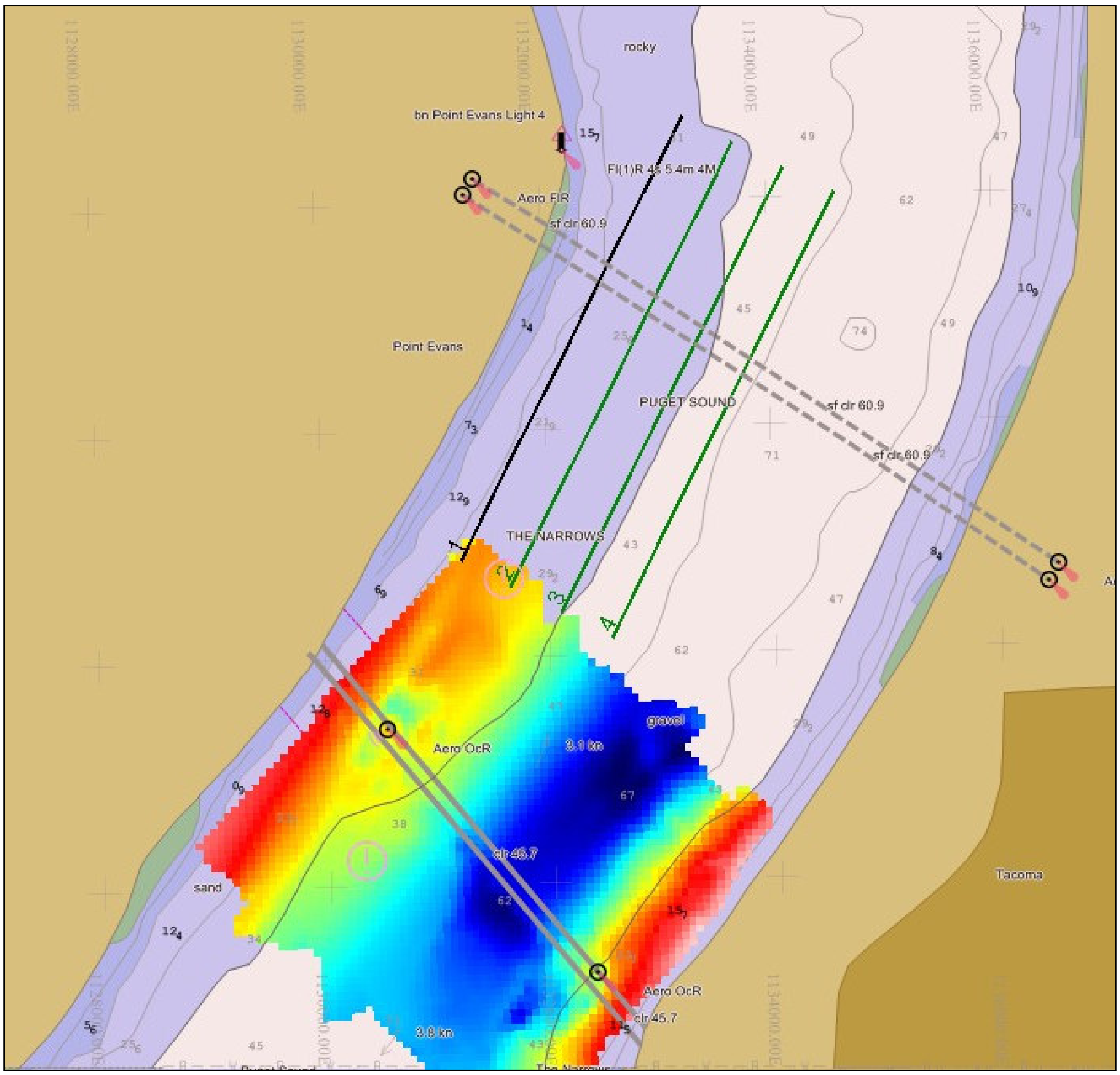
Estimated time for the survey is six days, preferably run over a neap tide period.

Costs are:

Mob/demob	$23,500
Operations	$72,900
Report	$ 7,200

During the project WAI was conducting a survey around the Narrows Bridge for the Tacoma Bridge Constructors. WAI added four additional survey lines in the Point Evans area and collected the data. The survey lines cover about 2/3 of the turbine array site designed by Coast and Harbor Engineering. The lines are shown in Figure 61. The data has not been analyzed as Tacoma Power stated that further work on surveys is not warranted now. The data is held by WAI and is available, with analysis, for $5000.

Figure 61: Site Survey Transect Lines

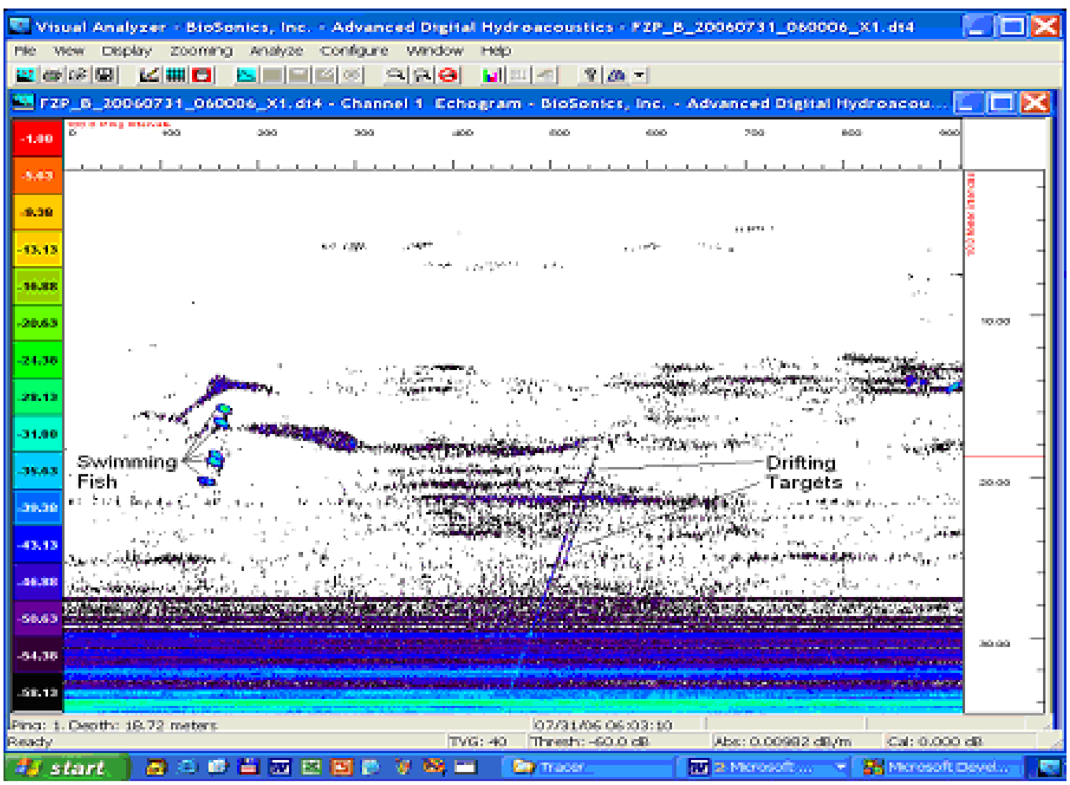


5.4 Water Column Monitoring

It is currently unknown how often large, submerged objects drift through the Tacoma Narrows. These objects may include boulders, deadhead logs, fishing nets, debris or even large marine mammals, and could potentially strike the turbines installed in the Narrows. Therefore, it is important to know how often such large objects pass through the Narrows, and at what depth, to help determine optimal turbine placement locations.

BioSonics, Inc. is a Seattle company that specializes in hydroacoustic observation of fish, submerged vegetation and other aquatic life. Using multi-beam sonar equipment enables quantitative, calibrated data to be collected on the presence and passage of fish. Figure 55 shows a hydroacoustic image from a site with fish and drifting targets identified. This data can be seen in real time as well as be recorded and analyzed over time.

Figure 62: Hydroacoustic Image of Fish and Other Targets



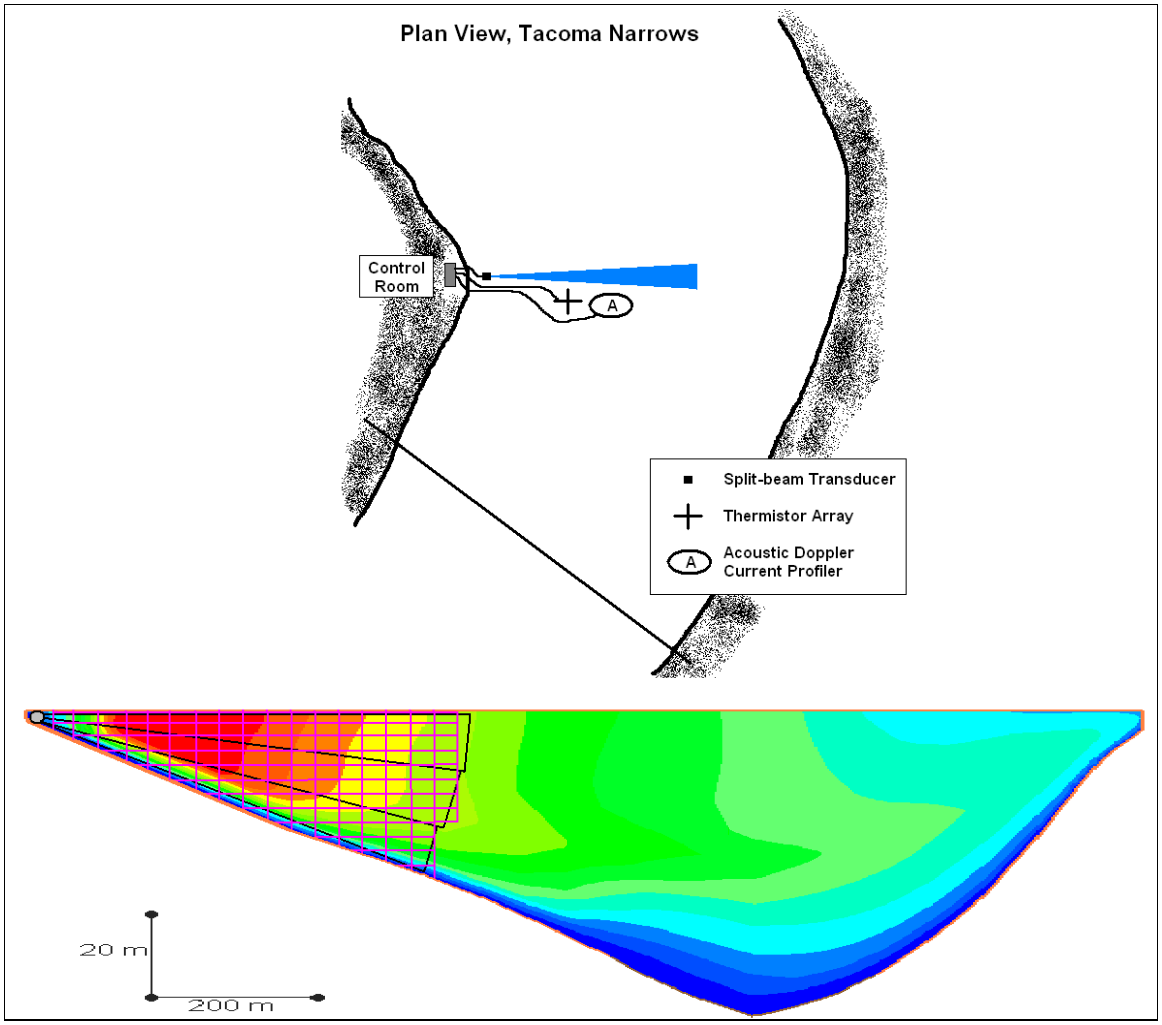
BioSonics is currently working closely with Verdant Power, and state and federal regulatory agencies on the Roosevelt Island Tidal Energy (RITE) project in New York City's East River. The BioSonics scientific and engineering team designed built and installed an automated hydroacoustic monitoring system at the site that provides continuous coverage of the underwater environment throughout the turbine field. The system has been in non-stop operation since the first turbines were installed in the fall of 2006. As fish and other marine life pass through the turbine field, the BioSonics monitoring system automatically tracks and documents the location and behavior of each individual relative to the zone of risk at each turbine. Advanced real time, unmanned data processing and reporting techniques developed by BioSonics provide hourly reports of aquatic species activity. The ability of the monitoring system to provide this continuous, comprehensive knowledge about the project's impact on the biological community has proven to be a critical factor in the permit approval process.

BioSonics was requested to evaluate the long-term deployment of an automated, unmanned, hydroacoustic monitoring system for the tidal turbine array in Tacoma Narrows. In addition to quantifying the trajectories of large objects capable of damaging turbines, a long term monitoring study will also provide a base line assessment of marine species abundance, distribution, behavior and migratory patterns in the Tacoma Narrows. This knowledge will also be crucial in determining optimal turbine placement to minimize possible negative impacts of the turbine field on animals passing through or living in the vicinity.

Once a pilot turbine or group of turbines is deployed, the hydroacoustic monitoring system could be expanded or reconfigured to monitor the specific region around the turbine with particular focus on the zones of high risk around the turbine blades, to assess the occurrence of marine species injury due to blade strikes.

The full BioSonics report is attached at Appendix 3. Figure 63 shows the proposed acoustic coverage area. BioSonics estimates that a 12-month monitoring study for both fish and inanimate drifting objects would cost approximately $350,000. It is unknown whether agencies would require that a turbine array have some kind of full time hydroacoustic monitoring.

Figure 63: Location of Proposed Turbine Array Hydroacoustic Monitoring System



5.5 Commercial Tidal Power Plant Construction Cost

EPRI estimated the construction costs of a commercial-scale tidal turbine project at about $100 million for 64 double-rotor turbines (Figure 64).

Figure 64: EPRI Cost Estimate for Commercial - Scale Tidal Turbine Project

	$/kW	$/Turbine	$/Array	%	Note
Power Conversion System	$660	$472,665	$30,250,532	29.2%	1
Structural Elements	$845	$605,062	$38,723,977	37.4%	2
Subsea Cable Cost	$18	$12,699	$812,705	0.8%	3
Turbine Installation	$450	$322,406	$20,633,956	19.9%	4
Subsea Cable Installation	$208	$149,093	$9,541,969	9.2%	5
Onshore Electric Grid Interconnection	$76	$54,688	$3,500,000	3.4%	6
Total Installed Cost	$2,258	$1,616,612	$103,463,138	100%	
O&M Cost	$49	$35,313	$2,260,052	59.3%	7
Annual Insurance Cost	$34	$24,249	$1,551,947	40.7%	8
Total annual O&M cost	$83	$59,562	$3,811,999	100.0%	

In comparison our study concludes that an installed cost per turbine might be about $1.5 million. An array of 88 turbines with 176 rotors, described in the power estimation section, might cost about $130 million. Using the EPRI estimate of about $60,000 a year per turbine, annual O&M for 88 turbines would cost $5,280,000.

Other estimated costs associated with construction would include:

Hydroacoustic monitoring system per BioSonics estimate: $350,000
Survey data analysis by Williamson Associates: $5000
Additional engineering by Coast and Harbor Engineering and Manson Construction: $200,000
Environmental Studies prior to Pilot Project: $830,000
Environmental Studies during the Pilot Project: $2,500,000
Environmental Studies during Commercial Operations: $2,900,000

But in reality, there is no professional basis for estimating costs at this time. There are no developers of devices of appropriate size who can even quote a price for their systems. No tested, warrantied systems are likely to be available for at least ten years. There is no data at all on long-term operations and maintenance costs of any tidal turbines tested to date. Any cost estimates are simply guesses and should not be used for making significant investment decisions.

For this study, the estimates above were used to develop a Cost of Energy model for the turbine array of 88 double-rotor turbines at $1.5M each and annual O&M costs per turbine of $60,000. This is presented below with the necessary caveats.

6 Environmental Issues

(Note: This section is authored by Meridian Environmental LLC and is included in whole).

The construction and operation of a non-federal hydrokinetic project in the Tacoma Narrows will necessitate a license under the Federal Energy Regulatory Commission (FERC). If Tacoma Power chooses to pursue a license for a five-year Pilot Project or a license to install and operate a commercial project, it will be required, at some point in each process, to prepare a Preliminary Application Document (PAD); solicit study requests from the resource agencies, the tribes, or interested members of the public; prepare detailed study plans addressing key resource issues; conduct studies and monitoring activities; and ultimately prepare a Draft and Final License Application.

The presence of several Threatened and Endangered Species in the proposed project area will also dictate a careful assessment of potential project effects on these species, as well as the issuance of two Endangered Species Act (ESA) Biological Opinions (from the National Marine Fisheries Service and US Fish and Wildlife Service). In addition, the Washington Department of Ecology (Ecology) will require a Section 401 Water Quality Certification, the US Army Corps of Engineers (USACE) will require a Section 404 dredge/fill permit, and a local lead agency will require a State Environmental Policy Act (SEPA) review.

Subsequent to the filing of the Pilot Project License Application or the Final License Application, FERC will also issue either an Environmental Analysis (EA) or Environmental Impact Statement (EIS) and ultimately a license for the proposed project. A detailed review of these and other permitting requirements and processes needed to receive a tidal project license in North America is provided in an EPRI report titled *Instream Tidal Power in North America, Environmental and Permitting Issues* (DTA 2006).

Figure 65 summarizes the permitting requirements relevant to the Tacoma Narrows Tidal Project. A discussion of environmental studies and monitoring activities potentially required to meet these regulatory requirements for a tidal project in the Tacoma Narrows are presented below. To facilitate review, we have separated our discussion into three categories: Studies Potentially Required Prior to Installing a Pilot Project (Baseline Studies); Studies Potentially Required During Operation of a Pilot Project; and Studies Potentially Required During the License Term of a Commercial Array. The permitting processes and issues for a pilot project versus a commercial array are likely to be similar or the same.

Figure 65: Required Pilot Project Permits and Time Frames

Level	Agency	Permit	Topic	Additional Requirements	Months
State	WDNR	Aquatic Use Authorization	JARPA Component	Requires a SEPA decision, HPA, BA, and other JARPA components	6 mo - 1 yr**
	WDOE	Section 401 Water Quality Certification	JARPA Component		1 yr +**
		Coastal Zone Management	JARPA Component	Requires a SEPA decision, BA, Section 401 certification, and other JARPA components	6 mo - 1 yr**
		SEPA (State adopts FERC NEPA)	NEPA EA/EIS		1.5 yrs
	WDFW	Hydraulic Project Approval	JARPA Component	Requires a SEPA decision, BA, and other JARPA components	45 days**
	DAHP	Archaeological Excavation Permit	(unknown whether required)		45 - 60 days**
Federal	NMFS	Section 7 Incidental Take Permit (Biop)	ESA/MMPA (Section 7)		1 yr +**
	USACE	Section 404 Dredge/Fill Permit	JARPA Component	Requires a SEPA decision, BA, Section 401 certification, and other JARPA components)	6 mo - 1 yr**
		Section 10-Work in Navigable Water	JARPA Component	Requires a SEPA decision, BA, Section 401 certification, and other JARPA components)	6 mo - 1 yr**
	FERC	FERC License for a pilot project	Federal Operating License	All studies, Section 401 certification application, BA, CZMA, study and monitoring plans	3 yrs
	FWS	Section 7 Incidental Take Permit (Biop)	ESA (Section 7)		1 yr +**
	USCG	Private Aids to Navigation	JARPA Component		3 mo**
Local	County	Shoreline Conditional Use	JARPA Component*	Requires a SEPA decision, BA, and other JARPA components	30 days**
		Shoreline Substantial Development	JARPA Component*	Requires a SEPA decision, BA, and other JARPA components	30 days**
		Shoreline Variance Permit	JARPA Component*	Requires a SEPA decision, BA, and other JARPA components	30 days**

Multiple federal and state regulatory agencies joined forces to create one application for use in applying for more than one permit at a time. It is titled, "Joint Aquatic Resources Permit Application (JARPA)".
* May be covered under existing permits for switchyard.
** After License Application is filed with FERC.

6.1 Studies Potentially Required Prior to Installing a Pilot Project (Baseline Studies)

The development of a license application for a commercial project requires that the applicant provide a description of the proposed project facilities, equipment, and operation and maintenance; an environmental analysis by resource area; and measures for the protection, mitigation and enhancement of the resources affected by the project based on a suite of site-specific studies. A license application for a Pilot Project contains much of the same information as the commercial application, but waives the majority of pre-filing studies and therefore the protection, mitigation and enhancement measures, in favor of detailed study and monitoring plans to be executed during the Pilot Project testing phase.

Because the affects of a tidal project on the natural and social environment of Puget Sound are largely unknown, we anticipate resource agencies, and the interested members of the public will recommend or require at least some level of monitoring during operation of the proposed pilot project (in lieu of traditional mitigation measures). The monitoring activities will serve to identify any potential project effects on a given resource and guide in the development of future mitigation measures or adaptive management strategies needed during installation and operation of a larger commercial array. Although the study/monitoring plans included in the pilot project license application will be developed in close consultation with the resource agencies and other stakeholders, we anticipate the need to monitor project effects on water quality, fish entrainment/migration, marine mammals, and sea birds (Figure 66). These monitoring activities will likely occur over a 2 to 5 year period during operation of the Pilot Project.

When a project proponent submits an application for a Pilot Project License to FERC, we anticipate that the resource agencies and tribes will want site-specific baseline information and studies before issuing the permits needed by FERC to issue a license. Although the Pre-Application Document and the License Application will each contain a thorough description of the known environment from existing literature, the agencies will want this site-specific information to consider potential environment effects on important resources; develop any necessary mandatory conditions under Sections 10(j), 10(a) and 18 of the Federal Power Act (FPA); and provide information needed to understand the extent of ESA-listed species in the project area and determine the anticipated amount of "take" during periods of project operation (needed for issuance of a Biological Opinion).

Although the effects of tidal power on the natural and social environment are only beginning to be explored in the Pacific Northwest, installation and operation of a pilot project near Point Evans will potentially affect marine fauna (including ESA listed fish and marine mammals); aquatic habitat (including designated critical habitat); recreation; commercial, recreational, and subsistence fishing; terrestrial vegetation, near shore vegetation and invertebrates, seabirds, aesthetics, current flow, sediment movement, water quality, commercial boat traffic, and cultural resources. A general description of many of these important resources is presented in the environmental report included on the CDROM.

To address these issues, we have identified 15 baseline studies that may be required prior to installing a Pilot Project (Figure 66). It is likely that the scope of these studies will be fairy limited during the initial pilot phase, and will focus only on those areas likely to be directly affected by the project and its associated transmission facility. In some cases, baseline information needs can be addressed through a detailed literature review (i.e. effects on commercial boat traffic). In other cases, baseline studies will require a substantial amount of on-site surveys and monitoring activity; although, we anticipate these more complex baseline studies could be completed within a year.

Our estimated cost of conducting these baseline studies and preparing the license application, including agency consultation and public involvement meetings, is $831,000 (Figure 66).

Figure 66: Studies Potentially Required Prior to Installing a Pilot Project (Baseline Studies)

Study Type	Study (potentially required by FERC prior to installing a test unit)	Cost
Permitting Documents	FERC License Application for Pilot Project (and supporting monitoring plans), NEPA EA/EIS, Section 401 Application, and Section 7 Biological Assessments.	$300,000
	Misc. Other Permit Applications	$20,000
Baseline Studies	Baseline sediment characterization	$50,000
	Baseline recreation use study (primarily fishing)	$15,000
	Evaluation of potential effects on commercial fishing	$10,000
	Detailed review of existing fish and marine mammal information for the proposed project area (as needed to identify any data gaps)	$25,000
	Baseline aquatic habitat surveys (including benthic characterization)	$60,000
	Baseline fish distribution and abundance surveys (including TES species)	$100,000
	Baseline marine mammal surveys	$40,000
	Detailed review of existing seabird information for the proposed project area as needed to identify any data gaps	$8,000
	Baseline seabird surveys	$20,000
	Study of seabird forage species	$8,000
	TES plant surveys and wetland delineations (cable/transmission line)	$15,000
	Near shore vegetation and invertebrate surveys	$15,000
	Aesthetics evaluation	$5,000
	Evaluation of potential effects on cultural sites and historic properties	$15,000
	Study of effects on commercial boat traffic	$5,000
	Agency consultation and public involvement meetings	$120,000
Total Cost		**$831,000**

6.2 Studies Potentially Required During Operation of a Pilot Project

While there is considerable uncertainty surrounding the studies that will be requested or required during the installation and operation of a pilot project, we anticipate the need to monitor the project's direct effects on aquatic habitat quality, fish, marine mammal and sea bird distribution and abundance, water quality, recreation, and noise, electric and magnetic fields (EMF), and vibration (Figure 67). We also anticipate the need to model the effects of a proposed commercial array on current flow and dissolved oxygen concentrations throughout the southern portion of Puget Sound.

These monitoring and modeling activities will also likely occur over a 2 to 5 year period during operation of the pilot project. Concurrently, Tacoma Power will need to further define the extent and operation of its proposed commercial array, initiate consultation with the resource agencies and the tribes, and begin the formal FERC licensing process. The results of these studies will be incorporated into the Final License Application for a commercial array, Biological Assessments, and other material needed to permit and guide in the development of the project.

If deemed appropriate by Tacoma Power, the results of these studies could also contribute to the development of a comprehensive Puget Sound wide-assessment of the potential effects of tidal power on the physical, biological, and social environment. Ideally, this assessment will be completed in partnership with the federal or state government and other utilities interested in developing tidal power in Puget Sound.

Our estimated cost of conducting these pilot project studies and preparing the license application documents for a commercial array (including agency consultation and public involvement meetings) is approximately $2.5 million (Figure 67).

Figure 67: Studies Potentially Required During Operation of a Pilot Project

Study Type	Study (potentially required by FERC prior to installing a commercial array)	Cost
Permitting Documents	FERC License Application for Commercial Array (and supporting monitoring plans), NEPA EA/EIS, Section 401 Application, and Section 7 Biological Assessments	$450,000
	Misc. Other Permit Applications	$25,000
Potential studies required during operation of a pilot project (results integrated into the FERC License Application for a commercial array)	Model the effects of the proposed commercial array on current flow and dissolved oxygen concentrations in southern Puget Sound	$300,000
	Evaluation of fish, marine mammal, and large inanimate object movement in the proposed project area (assumes 1year study duration).	$350,000
	Evaluation of fish, marine mammal, and sea bird entrainment at the pilot project (extrapolate results to commercial array)	$250,000
	Water quality monitoring at the pilot project (turbidity and toxic substances) (assumes 5 year study duration)	$110,000
	Evaluation of potential commercial array effects on recreation (primarily fishing)	$50,000
	Additional aquatic habitat surveys at proposed commercial array sites (including benthic characterization)	$300,000
	Additional fish distribution and abundance surveys at proposed commercial array sites (including TES species)	$300,000
	Additional marine mammal surveys in the proposed commercial array project area	$200,000
	Evaluation of ambient noise, EMF, and vibrations levels and potential effects on fish hand marine mammals	$55,000
	Additional sea bird surveys in the proposed commercial array project area	$30,000
	Agency Consultation and public involvement meetings	$150,000
Total Cost		**$2,570,000**

6.3 Studies Potentially Required During the License Term of a Commercial Array

Although even more uncertainty surrounds the extent and nature of studies potentially required during the license term of a commercial array, we anticipate that the resource agencies would, at a minimum, recommend or require continued monitoring of water quality (including DO concentrations in southern Puget Sound); fish, marine mammal, and seabird movement and potential entrainment; aquatic habitat quality; and project effects on fish distribution and relative abundance (Figure 68). Most monitoring and would likely occur over a minimum 5-year period during installation and operation of the commercial array; although habitat quality and fish relative abundance would likely be monitored over a minimum of 30 years.

Our estimated cost of conducting these studies during operation of a commercial array is approximately $2.9 million (Figure 68).

Figure 68: Studies Potentially Required During the Commercial Licensing Period

Study Type	Study (potentially required by FERC during the license term of a commercial array)	Cost
Potential studies required during the license term of commercial array	Monitor the effects of the commercial array on current flow and dissolved oxygen concentrations (assumes 5 year study duration in lower Puget Sound)	$250,000
	Monitor water quality in the project area (turbidity ,DO, and toxic substances) (assumes 5 year study duration limited to the project area)	$250,000
	Monitor fish and marine mammal entrainment/migration (assumes 5 year study immediately following installation and every 5th year thereafter for 30 years)	$1,350,000
	Monitor sea bird entrainment/movement (assumes 5 year study duration in the project area)	$120,000
	Monitor fish habitat quality and fish relative abundance in the project area (survey every 5 years over a 30 year period)	$960,000
Total Cost		**$2,930,000**

6.4 Federal Regulatory Jurisdictions for Hydrokinetic Projects

The Federal Energy Regulatory Commission (FERC) has asserted its regulatory authority over hydrokinetic projects developed within the three nautical miles seaward of the shores of the United States. The Minerals Management Service (MMS) claims jurisdiction over ocean energy projects located beyond the three nautical mile limit. Although there were some cross-claims of jurisdiction initially, the two federal agencies are working to formalize, through a Memorandum of Agreement, this delineation of the regulatory boundaries.

Tacoma Power's proposed Tacoma Narrows Tidal Energy Project would fall under FERC's jurisdiction due to its location in the southern portion of Puget Sound, an inland marine waterway of the northern Pacific Ocean.

6.5 The Federal Energy Regulatory Commission Licensing Process

The FERC has been licensing hydroelectric projects since enactment of the Federal Power Act (FPA) in 1920. Over the ensuing years the FPA and the FERC regulations have been amended and updated as the industry has matured and new laws have been enacted pertaining to power sales, transmission and distribution, and the protection of natural resources. FERC's initial approach to the permitting and licensing of hydrokinetic projects was to apply its existing regulatory process for hydropower to the relatively new and untested technology associated with hydrokinetic projects. As interest in investigating the suitability of specific sites for installation of wave or tidal energy projects increases, the inadequacies of the current FERC process with respect to the new technology and largely unknown resource effects are becoming obvious.

6.5.1 Preliminary Permit

FERC's regulatory process for hydroelectric projects involves a three-year period under a Preliminary Permit while an applicant: 1) evaluates the feasibility of a project; 2) consults with the resource agencies and other interested stakeholders on possible impacts of the project; 3) conducts studies to identify appropriate mitigation measures; and 4)prepares an Application for an Original License to construct and operate a commercial project for a period of 50 years.

While a Preliminary Permit grants the holder priority status over a potential project site for three years, the regulatory requirements to perform studies, consult, and develop detailed plans for the installation, operation and monitoring of a commercial project during this three-year time period are very labor, cost and time intensive.

As the national interest in renewable energy sources accelerated, it quickly became clear to those with an interest in evaluating wave or tidal project feasibility that the state of the technology was not developed to the degree that would facilitate decision-making and that the FERC regulations and timelines for the licensing of a hydroelectric project would not fit the state of development of the hydrokinetic industry.

6.5.2 Hydrokinetic Pilot Project Licenses

In February 2007, FERC called for comments on its preliminary permitting and licensing process as applied to hydrokinetic projects. The major theme of all comments FERC received was that the existing schedule-driven licensing process should not be applied to untested technology with unknown economic and environmental effects.

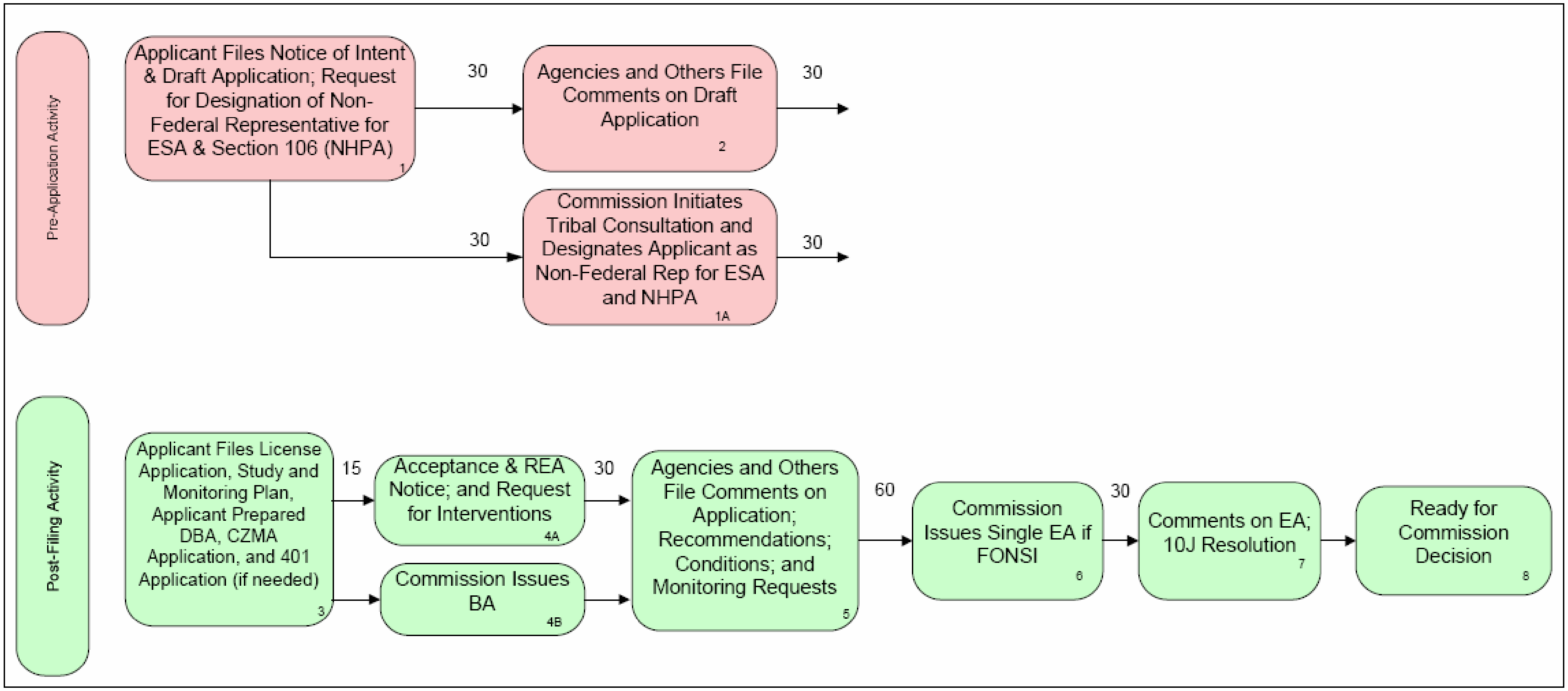
In response to these comments, FERC proposed, in August 2007, that a five-year Pilot Project License be established to allow for the in-water testing of hydrokinetic turbines and to study the affects of these generating units on the natural environment. FERC envisioned that within six months of receiving an application it would issue a license for a Pilot Project, and that all required federal, state and local permits would also be issued within this time frame. This would allow a potential developer to deploy and test one or more hydrokinetic generating units (with a total maximum generation of 5 MW or less) and conduct all studies to evaluate environmental effects post-license issuance (see table on following page). FERC followed the announcement of this proposed Pilot Project License process with a technical conference in Portland, Oregon on October 2, 2007.

The general consensus of FERC's proposal from the energy industry was that five years did not provide the time necessary to test the emerging technologies, many of which are still in the development stage. Concern was also voiced that FERC's Pilot Project License proposal is a separate process from the licensing process for a commercial array, but many of the component steps are identical. This would not lead to a coordinated and logical progression from the Pilot License phase to a commercial array installation, but rather a restart of the process with extensive duplication of effort and cost. Industry representatives are interested in seeing a transition that supplements the information gained and the consultation conducted during the testing period. Also, given the high up-front cost of deploying one or more pilot units and the limited testing and operating periods afforded by a Pilot Project License, the investment community would likely find the hydrokinetic technology too risky at this time.

During this October 2nd technical conference, the federal and state resource agencies had the opportunity to discuss their impressions and concerns with FERC's approach to licensing hydrokinetic projects. While the agency view in Oregon was much more proactive and prone to supporting a Pilot Project License conditioned with environmental studies and monitoring and a clause that would require that a project be shut down quickly at any sign of a negative impact, those agencies having jurisdiction in Washington State seemed to take an opposing view. In general, they stated that their agencies would not be able to issue the required permits without first having extensive data documenting the impacts of a specific hydrokinetic project, as well as possibly a programmatic environmental impact statement that analyzed the downstream effects of multiple projects in the Puget Sound region. The most critical of these permits is the "take" permit issued by the National Marine Fisheries Service (NMFS) under Section 7 of the Endangered Species Act, and the Section 401 Certification issued by the Washington Department of Ecology (Ecology) under the Clean Water Act. FERC is unable to license a project without both of these permits in place.

PROPOSED LICENSING PROCESS FOR HYDROKINETIC PILOT PROJECTS

Purpose – *To develop a pilot project licensing process that can be completed in as few as six months, provides for Commission oversight and agency input, and allows developers to generate while testing.*
(Source: Federal Energy Regulatory Commission, August 2007.)



FERC is currently accepting comments on its proposed Pilot Project License process and appears to understand the challenges that both the state of the technology and its proposed process pose to potential developers. FERC has given no date when it will respond to the comments or issue a new Pilot Project License process, but it is likely that there will be some changes. The most likely change will be an extension of the Pilot Project License term. Although both industry and the resource agencies appear to favor a 10 to 15 year license term, FERC will most probably come in with a 7 to 8 year term. It is also possible that FERC will revise its stance on what studies are required when and include a requirement that an applicant consult with the resources agencies and conduct those baseline studies deemed necessary to issue the required permits.

6.5.3 Integrated Licensing Process

Whether a hydrokinetic project proponent seeks a license to install and operate a commercial generating array at the end of the three-year period covered under a Preliminary Permit, or at the end of the testing and evaluation period afforded under a Pilot Project License, the Final License Application for a commercial installation will, at this time, be developed following FERC's regulations for the Integrated Licensing Process. Although FERC has two other licensing processes available, an applicant must petition FERC for approval before using either. It is unlikely that FERC would find, in the foreseeable future, that any hydrokinetic project would meet the "non-controversial and issue-less" criteria required to use the Traditional Licensing Process, or "ripe for timely and inclusive settlement of all issues" required to use the Alternative Licensing Process. Instead, a project proponent should proceed anticipating that a license for a commercial hydrokinetic project would be developed using the schedule-driven Integrated Licensing Process (ILP).

FERC adopted the ILP to address the delays frequently encountered with the other two licensing processes in having the information available in a timely manner to make licensing decisions. The ILP takes place over a three-year timeframe and integrates the pre-filing consultation with FERC's National Environmental Policy Act (NEPA) scoping requirements; increases FERC staff assistance during the study and consultation period; increases public participation; puts FERC in the role of approving or disapproving requests for specific studies; incorporates mandatory study dispute resolution, and establishes enforceable internal process deadlines. The information and consultation requirements are challenging over such a short time span with three major documents to compile and distribute (the Pre-application Document, the Preliminary License Proposal, and the Final License Application); and two years of studies to conduct with interim, progress, and final technical reports.

6.6 The Status of the Tacoma Narrows Tidal Power Project

Tacoma Power filed an application with FERC for a Preliminary Permit to investigate the feasibility of a tidal generation project in the Tacoma Narrows on September 15, 2005. The FERC issued a Preliminary Permit to Tacoma Power on February 22, 2006. The permit expires on February 1, 2009. The Preliminary Permit requires that Tacoma Power file with FERC every six months a report documenting that substantial progress has been made in evaluating the feasibility of the potential project and that stakeholder consultation is underway to address issues and concerns with the project. These progress reports have been filed as required.

FERC had only issued two Preliminary Permits for hydrokinetic projects prior to Tacoma Power's permit. At the time, there was no prospect for a Pilot Project License. In order for Tacoma Power to maintain its priority status on the Tacoma Narrows site, it would have had to embark on the ILP as soon as the permit was issued. This was not a feasible or prudent action to take in light of the infancy of the technology development and its unproven reliability. Also, no baseline information existed to assist Tacoma Power in the selection of a site best suited for tidal generation. The suitability of the currents and bathymetry of the Tacoma Narrows to support tidal generation had never been investigated. It would likewise have been impossible to quantify the effects of a tidal turbine on the natural environment and determine potential mitigative measures without knowing whether the technology would work and where it would be sited.

Since it appears evident that FERC will initiate some measures to modify its current licensing process to accommodate a new and untested renewable energy technology, as evidenced by its proposed Pilot Project License process, potential licensees may have the additional time necessary to test the existing hydrokinetic generating units, while participating in the development of a proven and reliable energy source. At the same time, the interaction of multiple types and configurations of generating units with the natural environment can be monitored and studied.

Tacoma Power's Preliminary Permit expires on February 1, 2009, 14 months from now. While it's evident that the time is not right to file an application for a license to install and operate a commercial tidal array in the Tacoma Narrows, there are several options open to maintaining a priority status on the Tacoma Narrows site while continuing to investigate the feasibility of generating reliable and economically viable power from the tidal currents.

A Second Preliminary Permit

Under FERC's regulations governing a Preliminary Permit, preference is given to a municipal applicant over others seeking an initial permit. If a three-year Preliminary Permit expires without the permit holder filing an application for a commercial project, the site is again open to competition. FERC's regulations do not expressly prohibit the initial permit holder from applying for a second permit term, although the municipal preference no longer plays a part in determining who will receive the subsequent permit. FERC's decision is usually based on the first viable permit application through the door, and it is not likely to be issued to the incumbent unless extenuating circumstances prohibited them from successfully completing an Application for an Original License.

In side bar conversations with FERC staff, they have indicated that a second Preliminary Permit term for a project proponent may be viewed more liberally for hydrokinetic projects, and that they would be willing to discuss the need for a second permit term on a case-by-case basis. The expectations for feasibility evaluations and stakeholder consultation would be greater than during the first permit term and would be reviewed with a "strict scrutiny" toward proactive advancement of the project.

A second Preliminary Permit term would give Tacoma Power an additional three years to evaluate the feasibility of a project in the Tacoma Narrows; however, it would not allow for the in-water testing of generating units. It is also likely that the resource agencies and other stakeholders would not be interested in continued consultation without some effort and commitment from Tacoma Power to conduct baseline studies during the permit period.

6.6.1 Pilot Project License

An alternative to a second Preliminary Permit term is to prepare and submit an application for a Pilot Project License. The effort would be fairly intensive during the remaining 14 months of the Preliminary Permit and would require preparation of a Pre-application Document (PAD) and a Final Application for a Pilot Project License. The PAD is a document that describes, to the extent possible, the type and number of hydrokinetic generating units expected to be tested during the license term, and the known existing environment. It is not intended that any studies be conducted during preparation of the PAD. A recent and thorough assessment of the natural environment in southern Puget Sound, prepared by the Department of the Navy in 2006, can provide much of the information required for the PAD[20]. The License Application summarizes the information presented in the PAD, documents stakeholder consultation, presents the applicant's proposed study and monitoring plans for the term of the Pilot Project License, and explains the applicant's reason for not including any study proposed by a stakeholder.

FERC initially thought that this Pilot Project License process would allow for the issuance of a five-year license within six months. Based on the positions taken by the resources agencies, the permits needed from these agencies before FERC can issue a license will not be forthcoming for a much longer time frame, and may require that Tacoma Power conduct some baseline studies prior to their issuance. With the filing of a Final Application for a Pilot Project License, Tacoma Power maintains a hold on the Tacoma Narrows site until FERC is able to make a decision on licensing the project. It is reasonable to assume that FERC would issue a Pilot Project License following receipt from NMFS and Ecology of a "take" permit and a Section 401 Certification, respectively; neither of which is likely to occur for two to three years following submittal of the application for a five-year Pilot Project License.

With such anticipated delays prior to the issuance of the Pilot Project License, and the five-year term of the license, Tacoma Power would gain an additional seven to eight years to study the feasibility of the Tacoma Narrows Tidal Project. This appears to provide the most reasonable approach should Tacoma Power wish to continue investigating the possibility of adding tidal power to its renewable energy mix.

6.7 Future Actions

If Tacoma Power decides that a second Preliminary Permit term is the best course of action, conversations should begin with FERC staff immediately to determine whether this is a viable option and to understand the conditions that might be placed on a second permit term. The cost of pursuing a second permit would be negligible, consisting of telephone communications and a possible trip to FERC's Washington D.C offices, and the preparation of a Preliminary Permit application. The application could simply involve an update to the document submitted in 2005, unless FERC adds additional criteria. By initiating this communication immediately, Tacoma Power will be able to quickly determine whether this is the best course, and if not, pursue an alternate approach.

[20] Department of the Navy. 2006. Marine Resources Assessment for the Pacific Northwest Operating Area. Pacific Division, Naval Facilities Engineering Command, Pearl Harbor, Hawaii. Prepared by Geo-Marine, Inc., Plano, Texas.

The cost and time factors of preparing an Application for a Pilot Project License are substantially greater, but this course of action protects the potential project site for much longer and allows for active testing of different technologies. As we anticipate that NMFS and Ecology will require that some level of baseline studies be conducted before they will issue their permits, we have provided an estimate of the potential studies and their costs, as well as the cost of preparing the Application for a Pilot Project License in the following Section 8.0.

We have also estimated the potential studies, and their cost, that may be required during the term of a Pilot Project License, and the cost of preparing a Final Application for a commercial tidal array. This is followed by an estimate, based on current observations, of the monitoring that may be required by Tacoma Power during the term of a commercial license.

7 Cost of Energy

This chapter is the Executive Summary of the full report on cost of energy prepared by Resource Dimensions, Inc. The full report is Appendix 4.

Tacoma Power is a municipal utility that will be required to meet the I-937 mandate. While their generating asset portfolio is substantially composed of clean hydroelectric power plants, they lack facilities eligible to produce RECs. Tacoma Power has three options: (1) look to the REC market to acquire the necessary RECs; (2) pay the penalty price, or; (3) expand their portfolio to include REC eligible power plants. This feasibility study is part of the effort by Tacoma Power to determine a course of action and provide the best response in serving the interests of Tacoma, Washington ratepayers.

This economic feasibility analysis is based on calculating and comparing levelized cost of electricity (COE) from a proposed tidal power plant to be deployed in the Tacoma Narrows. The standard used by the electric supply industry to evaluate the economic feasibility of a power plant is the levelized cost of electricity method. This is a monetary unit in cents per kilowatt-hour (¢/kWh) that allows comparison between different power projects with regard to plant generating capacity, project life, capital construction costs, annual costs, fuel costs, cost of capital, annual expenses, discount rates, etc. It is a common matrix by which to compare diverse and otherwise difficult to compare projects.

The analysis consists of calculating the COE for a baseline scenario and conducting sensitivity analysis based on changes to different project characteristics or assumptions: (1) a change in the Total Plant Investment (TPI) cost; (2) a change in the Annual Overhaul and Maintenance (AO&M), and (3) a change in the technical efficiency of the turbines, and (4) the best alternative renewable energy project, a newly constructed commercial-scale wind farm.

Summary of Cost of Energy (COE) Feasibility Analysis Findings

The baseline tidal power plant project as proposed is a best-case scenario. It has the following characteristics:

Baseline Scenario	
Rated Plant Capacity	22.43 MWh(a)
Annual Electric Energy Production	196,000 MW/year
Constant Dollars	2007
Commission Year (start of year)	2011
Book Life	30 years
Construction Financing	6.0% per annum
Debt Financing Bond	100%
Debt Financing Rate	6.0% per annum
Inflation Rate	3.0% per annum
Discount Rate	6.0% per annum
Cost of Insurance	1.5% per annum of Total Plant Cost
Efficiency of Turbine Array	50%

Number of Turbines	88 (double rotor)
Total Plant Cost	$138,770,000
Total Plant Investment	$145,560,000
Annual O&M	$7,830,000 per annum

Table 1 below shows that the cost of electricity for the proposed best-case tidal power plant is 8 cents per kilowatt-hour (8.0 ¢/kWh).

Table 1 Cost of Electricity (¢/kWh) – Baseline Scenario

Total Project Investment ($million)	145.6m
Levelized Annual O&M	
7.8m	**8.0** **(5.7)**
Nominal $2007*(Constant value)*	

The Total Project Investment (TPI) is the amount of permanent long-term capital financing for the tidal power plant. TPI is the initial upfront cost paid out to create the project. It amounts to $145.6 million. The Levelized Annual O&M (AO&M) cost includes all the expenses associated with operating and maintaining the project over its life, than levelized to an annual average. This recurring cost is $7.8 million. These two costs, TPI and AO&M, determine the cost of electricity (COE) that represents the minimum charge for electric power that must be collected for the tidal power plant to breakeven.

The COE for the baseline scenario is 8.0 ¢/kWh in nominal terms . The COE of 5.7¢/kWh, within parentheses, is constant or real terms .

Table 2 depicts the cost of electricity sensitivity analysis for changes in TPI costs projected for the tidal power plant designed for deployment in the Tacoma Narrows.

Table 2 Cost of Electricity (¢/kWh) – Sensitivity to Changes in Total Plant Investment

Total Project Investment ($million)	116.5m (20% decrease)	145.6m Baseline	174.7m (20% increase)	218.4m (50% increase)
Levelized Annual O&M				
7.8m (fixed)	7.2 (5.5)	8.0 (5.9)	8.8 (6.2)	10.0 (6.8)
% change in COE from Baseline	-10.0%	0.0%	10.0%	25.0%
Nominal $2007 *(Constant value)*				

For comparative purposes, Table 3 below shows the COE of a tidal power plant that would be competitive with a new build wind farm. The baseline scenario assumes, the tidal power plant is built and has a TPI cost of $145.6 million and an AO&M of $7.8 million. The analysis estimates the level of construction cost subsidies that would be required to decrease the TPI to be recovered to a level that the leads to a 5.0 ¢/kWh COE.

Table 3 Cost of Electricity (¢/kWh) – Equivalent COE to New Wind Systems

Total Project Investment ($million)	36.25m
Levelized Annual O&M	
7.8m	**5.00 (4.46)**
Nominal $2007 (Constant value)	

For the tidal flow power plant to be competitive with a newly constructed wind farm on a COE basis, the TPI cannot exceed $36.25 million. This means that a subsidy of $109.3 million would be required for the tidal power plant to produce electricity at 5.0 ¢/kWh. This represents a 75% reduction in Total Plant Investment.

Clearly, the tidal power plant under consideration is not economically feasible at this time. With a COE of 8.0¢/kWh for the best-case scenario baseline project and a COE of 7.0¢/kWh if TPI costs are reduced by 20% from the best case. The project, as proposed, cannot compete with many of the alternative renewable energy projects that currently can be deployed at commercial scale. However, over the medium-term, it is expected that as technological experience is gained, the "best-case" scenario will improve and the proposed project would become competitive.

8 Opportunities for Support

8.1 Objectives and Outcomes

Although it was not specified as a project deliverable, we have also identified potential funding sources to support a pilot project. The concern is that a pilot project will include about $3.3 million in cost for environmental studies and permit applications, in addition to the construction, operation and turbine acquisition costs. A budget of $5 – 6 million for a pilot project seems realistic even using the barge system described earlier. Considering that the pilot project might conclude that commercial power production is not economically feasible this is a significant risk to Tacoma Power. Therefore it is an objective to find other funding sources that could support a pilot project.

Another objective is to increase support by building knowledge about tidal power technology and environmental impacts through collaboration. Britain and Scotland are significantly further advanced in this area than is the USA. Scotland is the home of the European Marine Energy Centre (EMEC) where at least one turbine, the OpenHydro device, is being tested as of November 2007. In support of EMEC a coalition of UK and European organizations are developing standards for ocean energy devices and site development. During the Tacoma Power study contact was made with UK trade development officials to learn whether there could be collaboration between the UK, EMEC and Washington State to exchange and build knowledge.

Fortunately the outcome for this effort is promising. There are existing and pending Federal funding sources available for research on ocean energy development. At the State level work is underway to incorporate hydrokinetic energy as a qualified target for rate incentives, tax breaks and possibly grants.

A promising response was received from the UK Consul's office in San Francisco, California regarding international expert exchanges between Washington and the UK. Funding for this could come from both Washington and the UK. This is a good short term opportunity which could include members of the state congressional delegation who might increase their efforts to secure Federal funding for a pilot project.

8.2 Federal

Sean O,Neill, president of the Ocean Renewable Energy Coalition, provided the following report in August 2007 on Federal legislation to support ocean energy:

> "In the 2007 session of the US Congress, the House of Representatives passed H.R. 3221 and the Senate passed S. 6, both of which contain the central Research and Development (R&D) provisions of their predecessor bills, H.R. 2036, introduced by Congressman Jay Inslee (D-Washington) and S. 1511 introduced by Senator Akaka (D-Hawaii), Senator Murkowski (R-Alaska) and Senator Snowe (R-Maine). For the most part, these bills pro-

vide $50 million per year over 5 years for research and development primarily for advanced marine renewable energy systems and technologies. The bills also include provisions for DOE to create National Ocean Energy Research Centers.

The House bill also includes Coastal Zone Management modifications including transmission studies funding and site assessments. The Senate bill includes Renewable Energy Construction Grants and provisions specifically for geothermal and ocean renewable energy in Alaska.

The House of Representatives passed the energy tax bill H.R. 2776 that provides for 5-year extensions of the Production Tax Credits (PTCs) through 2012 for all qualified renewables. That bill includes ocean renewables for the first time; although the Energy Policy Act of 2005 (EPAct) did include ocean renewables in the Renewable Energy Production Incentives (REPI). REPIs can be seen as the equivalent of Production Tax Credits for municipal utilities that don't pay taxes. The recent energy tax bill also provides for ocean renewable energy in Clean Renewable Energy Bonds (CREBS). CREBS provide bonds for municipal utilities as well; however, both the REPI and CREBS programs have suffered from continued underfunding since their inception."

During project telephone interviews were held with staff from the US Department of Energy who are now involved in ocean energy program development. At the National Renewable Energy Laboratory, Walter Musial is leader of the Ocean Energy group. He is also the DoE alternate member delegate to the International Energy Agency's Implementing Agreement on Ocean Energy Systems. NREL has been working on offshore wind technology development for several years already.

According to Mr. Musial, the intentions of DoE around ocean energy are still in development. If federal funding is authorized and appropriated then DoE and NREL may have funds to support technology development. NREL is specifically interested to establish test sites for tidal, wave and offshore wind energy converters. The concept of a barge in Tacoma Narrows to test turbines was discussed and Mr. Musial said it was an idea that they would consider if funding becomes available.

Environmental studies needed for s
ite permits may be supported by DoE through the Pacific Northwest Laboratory in Richland, Washington, which has decades of experience studying impacts of hydropower generation on fish, in particular migrating salmon. PNL also maintains a marine laboratory at Sequim, Washington and has capabilities to conduct and/or direct marine environmental studies in Tacoma Narrows.

The US Navy has already established an ocean energy development program through the Naval Facilities Engineering Command and is testing wave energy converters in Hawaii. During this study interviews were held with senior staff at the Office of Naval Research in Washington DC. The Navy is interested in ocean energy conversion and is working now to expand and more officially formalize its ocean energy program. It does not yet include tidal energy. But during this project a proposal was made to the US Department of Defense, Environmental Security Technology Certification Program, for a private company to collaborate with the Navy to evaluate five different turbine rotors, and then test the best performing ones in Puget Sound with the Naval Undersea Warfare Center at Keyport, Washington. The proposal was not funded but the partnership remains viable and other sources of funding are being sought.

The Bonneville Power Administration is providing R&D funding for tidal power in its service area. It has already funded several projects including this Tacoma Power study. Funding is a 65% match not to exceed. 2008 funding has been allocated but funding for FY 2009 will open for proposals in March 2008. The BPA funding could support more engineering for a pilot project installation and initial environmental studies needed for a pilot project.

It seems likely that in 2008 a substantial amount of Federal funding will become available to support a pilot project in Tacoma Narrows. If Tacoma Power wishes to proceed then an important strategy will be in 2008 to formalize and communicate the development process, emphasizing the pilot project and testing facilities, and to aggressively pursue grant funding.

8.3 State

There are a variety of state incentives for renewable energy generation. Tacoma Power is fully aware of these and they need not be repeated here. New legislation in 2008 is unlikely because it is a short session and does not create a budget for the next year. However no pilot project needs to be initiated in 2008 because the existing preliminary permit application is in force until February of 2009. Therefore in 2008 Tacoma Power could work with state leaders to develop a strategy that would lead to bills introduced in the 2009 legislature that would fund projects. Targeted state funding thus could become available in 2010, which is about the time we expect that discussions with agencies would have resolved some concerns allowing a pilot project to go forward.

8.4 International

There is an extensive and growing international network on ocean energy development including environmental concerns. The most organized coordinating organization is the International Energy Agency's Implementing Agreement on Ocean Energy Systems. Twelve countries including the USA are represented on its Executive Committee. In Canada, which share nearly identical environmental conditions in BC with the Tacoma Narrows in Washington, the Ocean Renewable Energy Group is coordinating activities.

Regulatory uncertainty is a tremendous obstacle to progress for ocean energy development. Sharing information internationally is the best and most cost-effective way to reduce that uncertainty because everyone benefits from the most advanced analysis. Scientists in the UK have done much more than their North American counterparts on almost every aspect of ocean energy development. Their knowledge should be tapped to help USA regulators reduce uncertainty and move ahead faster.

During the project contacts were made with the UK Foreign Consulate Office in San Francisco which has already hosted several UK delegations on ocean energy to that region. As of conclusion of this project discussions are underway to design a two-way experts exchange on ocean energy for business executives, scientists and officials (details provided separately to Tacoma Power). The USA states of Oregon, Washington and Alaska could host a delegation from Britain and Scotland, and vice versa. Sites, agencies and companies can be visited. This could be a catalyst event to encourage other sources of funding for a Tacoma Power pilot project.

9 Conclusions

9.1 Technical Feasibility

1) It would take more than 100 15m-diameter tidal turbines to make 10 MW/hr output from the Tacoma Narrows. In comparison, Tacoma Power needs about 685 MW/hr to supply its 2005 base.

Any existing tidal turbine design, even in proposed status, of up to 15 m (50 ft) in diameter, with swept area of about 200 square meters, will produce at maximum only about 100 kW/hr *average annual* output in the Tacoma Narrows. To make 10 MW/hr output will take 100 or more of these large turbines. This corresponds with the EPRI findings in which 128 16m rotors would produce about 16 MW/hr, or 125 kW/hr per turbine rotor.

In comparison, the largest new commercial wind turbines are rated at 5 MW/hr each with average output of over 1 MW/hr each, or 8 times the power of a 16m tidal turbine which has never been even demonstrated, much less proven.

To achieve the maximum possible output, an array of turbines was designed for installation at Point Evans. If turbines were available now, it is technically feasible to install over 100 turbines, of several designs, in the array and generate power up to 10 MW.

2) There are no utility-scale tidal turbine technologies we could expect to implement successfully within the next five to ten years.

It will be at least three years, and maybe five, before any tidal turbine developers could reasonably be expected to have a working commercial-scale tidal turbine, 10m or more in diameter, available for demonstration. They will need to demonstrate a new working unit in operation for at least several years until a maintenance schedule can be established. We believe it may be five to ten years before tidal turbine technology is ready to come to Tacoma Narrows.

3) Tacoma Power may consider that the energy available is worth pursuing, at least to keep its options open. If so the best technical path is to let others test turbines until there are some that can actually survive a one-year test successfully. Such efforts are underway at EMEC and in the Bay of Fundy. Then those units could be tested in Tacoma Narrows. At this time it seems a barge installation is the best way to test devices to keep down costs and reduce regulatory obstacles. Meanwhile Tacoma Power should participate in technology development networks so innovations are monitored and better information obtained.

4) Tacoma Power should postpone further consideration of tidal turbine technology for about five years to allow for both technology and regulatory development. There are no commercial scale tidal turbines that could be demonstrated in 2008-2009 to the advantage of Tacoma Power, considering the cost and permitting / technology risk and studies required.

9.2 Economic Feasibility

The cost of energy for a project of maximum turbine density in the area of highest power is more than the cost of energy for competing sources such as wind. The project is not economically feasible without significant subsidy.

The economic feasibility is actually unknown because we cannot predict how many turbines would be allowed in any site. The area with the most power, at Point Evans, will require a densely spaced array of large turbines if it is to make more than 10 MW/hr. Any object drifting through this array will certainly interact with one or more turbines. We do not think such dense spacing will be allowed. But if half the turbines are removed, for example, the economics change drastically for the worse.

Nonetheless a sound effort was made to evaluate the economics of the best possible commercial scale project, using engineering to estimate installation costs, original estimates from the EPRI analysis, and sophisticated modeling of the Cost of Energy using sensitivity analysis.

The economics are most sensitive to installation and O&M costs. If these can be significantly reduced – by at least 50% - then the project economics improve. However there is no way to estimate the economics until the number of allowable turbines is determined, and this requires that the agencies respond to a permit application asking for the maximum density allowable. When they determine what will be allowed, then the economics can be calculated with reasonable accuracy.

Since the agencies control the economics via their control over turbine numbers, it could be to the advantage of Tacoma Power to proceed with an application for the maximum number of turbines. This will then require the agencies to evaluate and respond, probably to request studies of different types. Eventually they may allow a lesser number of turbines, at which time the economics can be estimated properly. But at this time we cannot tell what the agencies would actually do if confronted with this permit request. They may decide to postpone even considering it until Snohomish PUD declares its own intentions and the total number of turbines proposed in Puget Sound is known.

9.3 Environmental Feasibility

The environmental feasibility of a commercial scale tidal power array is unknown. A commercial turbine array will remove energy from the flows through the Narrows. It will not be much – the total power available at the transect of maximum energy is about 82 MW. The proposed maximum density turbine array would generate 10-15 MW, or about 15%. This is what EPRI estimated would be the maximum allowed extraction.

But even this much extraction is of concern because of the high sensitivity of the South Puget Sound marine environment to reductions in flows. To estimate potential impacts will take a comprehensive system-wide study of flows and circulation, which would take at least several years. We have provided a scope of work for a research planning meeting to identify the necessary studies.

The turbines turn at a relatively slow rate and are unlikely to impact fish. But they could impact marine mammals which cannot avoid them easily. This issue cannot be studied in theory, it can only be resolved by installing turbines and observing them. The installation would require a means for rapid removal of the turbines if impacts are an issue.

Even a commercial installation could be removed to leave basically no trace in the environment. Manson Construction confirms that piling driven into the seabed in the Narrows can be removed with a vibration technique that enables them to be pulled straight up. Submerged cables can be left in place or removed. In general we believe that the installation infrastructure will have no significant environmental impact. However it will of course create conflicts in use of space with others such as fishermen and scuba divers.

10 Recommendations

In December 2007 an important event for Tacoma Power occurred: The US Congress passed and the President signed an omnibus energy bill that includes $25 million per year for five years for ocean energy research and development. It specifically includes funding for test projects and necessary studies. The Washington State Congressional delegation is well-placed to help appropriate funds for projects in the state, and Tacoma Power has the most advanced study and project proposal available. It is likely that Federal funding will become available for Tacoma Power to conduct a pilot project; in which case it would be probably be necessary to demonstrate commitment by filing a pilot project license application.

At this time commercial-scale tidal power generation in the Tacoma Narrows is not feasible technically or economically. But this could change. The technology is advancing rapidly and significant cost decreases are expected. The political importance of developing local renewable energy resources could increase. Therefore Tacoma Power must decide if it wants to proceed at all with its investigation of the resource. If not then it should abandon its permit application. Perhaps another entity will step in to develop it and Tacoma Power can get power from it if it successful. This decision needs to be made relatively soon as the existing preliminary permit will expire in February 2009.

We recommend that Tacoma Power keep its rights to the site and make itself eligible for funding for technology development and permitting studies. This funding could be significant, providing benefits to the Tacoma community, creating new technologies that can stimulate economic development, and developing a renewable energy resource that could potentially power ten thousand homes. Tacoma Power can manage the process with relatively little of its own investment by involving partners such as the University of Washington and the local marine industry to implement a pilot project, paid for (hopefully) with federal and state funds.

One benefit not previously mentioned is that such an effort could help Tacoma Power get more energy from its existing hydropower sources. The technology for tidal turbines is quite innovative and developing quickly. There are likely to be applications for such turbines in the water flows around large dams and water systems. This could be a new source of relatively low-cost distributed generation that can help Tacoma Power provide its services.

10.1 FERC Licensing

Under normal FERC licensing procedures, an applicant with a preliminary permit applies for a commercial license at the end of the permit. But the technology and economics needed for a successful commercial project do not justify a full commercial license application for at least several years. Tacoma Power thus should consider its options to maintain development rights under FERC rules to the Tacoma Narrows site.

Tacoma Power has the option to FERC for another Preliminary Permit after the first one expires in February 2008. If Tacoma Power decides that this is the best course of action, conversations should begin with FERC staff immediately to determine whether this is a viable option and to understand the conditions that might be placed on a second permit term. The cost of pursuing a second permit would be negligible, consisting of telephone communications and a possible trip to FERC's Washington D.C offices, and the preparation of a Preliminary Permit application. The application could simply involve an update to the document submitted in 2005, unless FERC adds additional criteria. By initiating this communication immediately, Tacoma Power will be able to quickly determine whether this is the best course, and if not, pursue an alternate approach.

Should Tacoma Power wish to continue investigating the possibility of adding tidal power to its renewable energy mix it could apply for a Pilot Project License. With the necessary additional study periods added to the five-year term of the license, Tacoma Power would gain an additional seven to eight years to study the feasibility of the Tacoma Narrows Tidal Project. This will involve additional cost for studies but it ensures that the agencies are required to respond to the permit application and thus expedites the process. It also makes it obvious to potential funding sources that Tacoma Power deserves significant financial support to make the project successful.

10.2 Pilot Project

The most important objective of the pilot project is to initiate the regulatory review. The type of turbine is generally irrelevant at the early stages. The agency review of *individual* turbine impacts can be achieved with a minimal pilot project.

A pilot project could even be a small turbine suspended from a floating buoy and anchored in place. But the physical impact issues are size-dependent, obviously, so the test must be of individual full-size turbines.

In order to more easily test several different turbine designs we recommend a floating barge moored in place in Tacoma Narrows with a crane-like suspension to lower turbines into the flow and retrieve them easily. This is sufficient to initiate permit evaluation for turbine physical impacts on fish and marine mammals, conflicting uses of space, transmission cable placement and shore crossing and grid integration, and more. The barge platform provides space for on-site environmental monitoring.

The Verdant Power, OpenHydro, Lucid and UEK turbines appear to be the most ready for testing in a pilot project using the barge installation. We think they would all need at least a year of preparation time to make their turbines available. The OpenHydro design has the most promise, in our opinion, and could be tested first.

A pilot project would take about one year to design and engineer, one year to procure and install, and one to two years to operate. Construction and operation costs may range from \$3 to \$5 million. Permit study costs are estimated at about \$2.5 million. A pilot project would include the hydroacoustic fish monitoring system designed by BioSonics. It will enable remote full-time observation by sonar of objects and animals around the turbine.

Overall the pilot project budget should be estimated at about \$7 million. The relatively high cost for a pilot project here is justified by the fact that Tacoma Power will test competing turbine designs and agencies will produce permitting decisions in a nationally-observed project that will provide definitive answers for some key questions and will accelerate the development of this new technology. If done in partnership with the University of Washington, which is eligible independently for ocean energy research funding for environmental and other studies, Tacoma Power's budget share could be half the total.

We recommend that Tacoma Power develop a general scope of work and budget for such a project soon and make it available to interested funding organizations such as the US Department of Energy, the University of Washington and the Washington state congressional delegation. The budget should include the cost of a new full-time project manager on staff at Tacoma Power, as well as all other costs.

10.3 Developing Support

There is an increasing amount of financial support becoming available for tidal power project development and Tacoma Power is in an excellent position to obtain some of it.

There is a strong desire among funding authorities to see practical pilot projects underway. But there is also a need for the projects to be properly documented by objective institutions. Partnerships with universities in particular could make this successful.

The new ocean energy funding authorization specifically includes funding for universities to create technology development and testing programs. Several professors at the University of Washington (UW) are already involved with tidal power projects including this one, and are interested to continue their participation.

It is recommended that Tacoma Power initiate a partnership with the UW to conduct a pilot project. This should include development and testing of small (1-2 m in diameter) turbines that can be deployed from workboats, and estuarine modeling and impact evaluation studies. If the five-year pilot project license is granted there will probably be about 6-7 years for the partnership to develop a successful outcome. This partnership will be particularly attractive to funding organizations because of the advanced capabilities offered by the partners.

If a pilot project for testing full-size turbines is proposed, as described above, then the UW is the logical partner for research studies. Another good partner is Pacific Northwest National Laboratory. It has a marine science laboratory at Sequim, WA., and extensive experience evaluating the impacts of turbines on fish. It can be funded through the Department of Energy for such studies.

Tacoma Power could also develop support among traditional hydropower organizations and funders by examining the potential for the new tidal turbine technologies to be applied in existing large hydropower projects such as Tacoma Power's dams. The National Renewable Energy Laboratory and the Pacific Northwest National Laboratory would be particularly good partners for such an effort and it could help Tacoma Power get more power from its existing water systems and make it a national leader in new hydropower development, all as a low-cost spin-off of its tidal power studies.

10.4 Final Recommendation

The new ocean energy funding that has been authorized significantly "changes the game" for Tacoma Power's development of renewable tidal energy from Tacoma Narrows. Although the total power available from the Narrows is small in comparison to Tacoma Power's needs, further development of the resource can likely be achieved at little cost to Tacoma Power because other organizations will fund a well-designed pilot project. There are a variety of benefits to Tacoma Power from this approach and there is little cost or risk.

A pilot project should demonstrate the commitment to follow through should the project be successful. This is best achieved if Tacoma Power applies for a five-year FERC Pilot Project License. This could be done after applying for another Preliminary Permit application, which would give Tacoma Power about 7 years more control over the Tacoma Narrows site.

The following steps are recommended

1. Jan – May 2008: Design (at basic level) a pilot project and budget with the following features:
   - Clear statement of national benefits of proposed project
   - Partnerships with UW, US Dept.of Energy, others
   - Barge platform system to test a variety of turbine designs
   - Funding to support developers to come test their turbines
   - Estuary-wide study of circulation and potential impacts of energy extraction
   - Environmental monitoring, documentation and public education

2. May 2008: Submit pilot project design abstract to potential funders

3. Sept – Dec 2008: Request a second preliminary permit from FERC; receive funding appropriations, hire a project manager and issue RFPs for pilot project contractors.

4. Feb 2008 – Feb 2009: Submit proposed project to state agencies for permitting; continue with pilot project design and engineering.

5. Feb 2009: Apply for five-year FERC pilot project license. Continue with pilot project preparation and implement as soon as license is granted.

Appendix 1

HISTORICAL AND NEW CURRENT MEASUREMENTS IN TACOMA NARROWS, WA

FINAL REPORT

NOVEMBER 2007

PREPARED FOR

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HISTORICAL AND NEW CURRENT MEASUREMENTS IN TACOMA NARROWS, WA

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Historical and New Current Measurements At Tacoma Narrows, WA Draft Report

1.0 INTRODUCTION

The Tacoma Narrows is an area containing some of the highest currents speeds within Puget Sound. This is caused by the passage through the Tacoma Narrows of all marine water entering southern Puget Sound on each tidal cycle. It is also in part caused by the relatively shallow depth of the Narrows (approximately 230 ft. maximum depth) as compared to the maximum depths in the main body of Puget Sound (600 – 800 ft. depth). Due to the strong currents, large area of the Narrows, relatively shallow depths, and predictability of the tidal currents, the Tacoma Narrows makes an excellent choice to investigate the potential for generation of electrical power from current flows.

While the Tacoma Narrows has strong currents, the bends in the Narrows, as well as the hard turn the currents take passing Point Defiance during flood currents, all create significant variations in the strength and direction and level of current turbulence within the Tacoma Narrows. The current does not flow through the Narrows as a slab of water flowing at a uniform speed. Instead, there are eddies and significant cross-channel flow variations.

A preliminary study of the potential of the Tacoma Narrows for power generation (EPRI, 2006), suggested the area off Point Evans in the northern portion of the Tacoma Narrows would be appropriate to consider for power generation in part due to its proximity to transmission lines. As a first step toward evaluating the economic, engineering, and permitting feasibility of a tidal energy facility located with the Tacoma Narrows, Evans-Hamilton, Inc. (EHI) assessed historical current records and collected new current records. This data report covers historical current measurements primarily from 1977 – 1980 and new current measurements for 30 May 2007 to 3 August 2007. The report describes the instrumentation, data processing methods, and resultant data collected both for the historical and new measurements.

2.0 HISTORICAL MEASUREMENTS

2.1 Measurement Locations, Dates, and Sources

Historical measurements were gathered for the area north of Tacoma Narrows between Point Defiance and Gig Harbor to south of the Narrows Bridge. Initial review of the data revealed nearly fifty (50) historical current records for the area. These records were collected as early as 1917 to as late as 2003. All records dated prior to 1970 were not analyzed. These records were typically shorter than 4 days or are not available in electronic format. The measurements taken in 2003 for the construction of the new Narrows Bridge are proprietary data and cannot be analyzed for this report.

Table 1 lists the historical current records analyzed for this project. Measurement lengths were 15 days or longer. Figure 1 shows the locations of these sites. The historical sites have been given a site number consistent with the new current records. The three new sites are designated TP1 – TP3 (TP = Tacoma Power). The historical sites are numbered chronologically beginning with TP4 from north to south through the Narrows. These sites, TP4 - TP10, were collected by the National Ocean Survey (NOS) and Pacific Marine Environmental Laboratory (PMEL) of NOAA.

2.2 Typical Equipment and Mooring Designs

The historical measurements were collected using a wide variety of measurement devices. The earliest measurements were collected using drift poles attached to log lines (the length of line carried away from the anchored vessel by the pole in one minute equaled the current speed in knots). Through the decades technology progressed from single point electronic devices to the standard used today, acoustic Doppler current profilers (ADCP).

During the 1970's and 1980's the typical instrumentation were Aanderaa RCM4 current meters or AMF vector averaging current meters. Both meters work using similar sampling methods. Current speed is determined by counting the number of revolutions of a Savonius rotor during a preprogrammed sampling interval and current direction is determined from an internal compass aided by a large vane and gimbal assembly attached to the current meter to assist orientation. Data was recorded internally on magnetic tape. The meters were attached to a taut wire mooring with sufficient buoyancy and anchor weight to keep the mooring and meters vertical. Typical mooring design was two to three meters attached to the mooring line at 15 meters depth, 70 meters depth and 50 meters above bottom depth. Most moorings were deployed for greater than 30 days to allow tidal constituent analysis.

Beginning in the 1990's, the ADCP was introduced. The advantage of the ADCP was measurement of water currents at multiple depths using just one instrument. The ADCP has 3-4 acoustic transducers that transmit sound at a fixed frequency and listen for echo returns from scatterers in the water (Doppler shift). The multiple beams are used to measure three velocity components (east, north, and vertical) of the water movement yielding current speed and direction and upwelling or downwelling. Typical mooring design for Puget Sound is placing the meter with the transducer heads facing upward in a trawl resistant bottom mount (TRBM) placed on the seafloor.

2.3 Data Processing and QA/QC

The data has undergone data processing using EHI standard routines. To begin processing, the data were plotted and all obvious erroneous data points were flagged and removed from the final data files.

Data plots, tables, and text files have been generated for each data set with a record greater than fifteen days and nonproprietary. The organization of the data products within the appendices, along with notes concerning each type of data product, is provided below. All times are referenced to UTC.

The data plots and tables are provided in Appendix A. Text files of the processed data are available on a separate CD. File format and units are provided at the start of each data file. Flagged erroneous data or missing data are assigned the value 999.9. Date gaps in the data file are assigned 999.

Appendix A shows time series vector plots of the measured currents. For readability, data collected during the same time period have been plotted on the same page. Hence, TP6 and TP9 both measured data during March – April 1978 and are plotted together and TP8 and TP10 both measured data during February – March 1977 and are plotted together. In the vector plots, the length of the vector is equal to the speed of the current according to the speed scale (in cm/s). The direction of the vector equates to the current direction, with the current moving from the centerline toward the tip of the vector. North is towards the top of the paper, east to the right, south to the bottom, and west to the left.

For each current record, a table showing the percent of the measurements within 10 cm/s speed bins, and 20-degree direction bins, is provided. Directions are degrees True.

2.4 Data Quality and Quantity

Nineteen current records at seven sites through the Narrows had usable data. The records are clustered during two time periods, February – April and September – November. The majority of the data appears to be high quality. There are sections within four of the records that are questionable quality but without deployment logs it is only a guess as to the reason for the degradation in the data. Specifically these data sections include the 15 m record for site TP5, both depths for site TP6 near the beginning of April and the last part of the 5 m record, and the last half of the 43 m record for site TP10. Because currents for these sections of the records are so different from the remainder of each record we suspect the meter got tangled on the mooring line, the Savonius rotor broke or got stuck, or the vane was lost or somehow impacted.

3.0 NEW MEASUREMENTS EQUIPMENT AND FIELD PROCEDURES

As mentioned earlier, the area off Point Evans in the northern portion of the Tacoma Narrows would be appropriate to consider for power generation. To assess the specific current conditions surrounding Point Evans, new measurements of the currents were conducted using profiling current meters which provided measurements of the currents every 1m vertically at each measurement site, resulting in measurements of profiles of the currents every 15 minutes.

3.1 Measurement Locations and Dates

The new measurements were collected at three sites (Figure 2) for two month-long deployments covering 30 May to 2 August 2007. The measurement sites were chosen to identify both the along and across-shore variation of the current, as well as provide measurements in different water depths, and within different current conditions along the shore, for purposes of numerical model calibration.

Table 2 lists the dates and locations of each site. At site 2, currents during the largest tide range of the year (mid June) slid the bottom-mounted current meter approximately 900m southward (note red arrow in Figure 2), resulting in effectively obtaining measurements for two weeks at a fourth location (designated 2B in Table 2).

3.2 Instrumentation and Mounts

The ADCPs were installed within open cage bottom mounts as shown in Figure 3. Because of the nature of the current flow through the Narrows (fast currents and large cobble or rock sweeping through the area) and from EHI's past experience in the Narrows, the open cage was used. This would allow potential debris moving along the seafloor to not accumulate inside the bottom mount. These bottom mounts also include an acoustic release which releases a pop-up buoy and attached recovery rope, and a pinger to assist in locating the bottom mount precisely.

3.3 Mobilization and Deployment

Prior to deployment, all equipment was mobilized at the Evans-Hamilton, Inc. (EHI) Seattle facility. This included building the mooring components, replacing all batteries, bench testing all electronic equipment, and calibrating the current meter compasses. All instrument clocks were synced to Coordinated Universal Time (UTC). All equipment was then transported to Fishermen's Terminal and loaded aboard the deployment vessel.

The vessel was maneuvered onto the deployment location and the bottom mount was lowered to the bottom using the boat's A-frame. Once on the bottom, the location of the mount was recorded using a DGPS interface into a notebook computer. Verification of the mount position is made by triangulating on the acoustic pinger located on the mount. All three mounts were deployed on 30 May 2007.

3.4 Servicing and Recovery

The service cruise for all the mounts was scheduled for 2 July 2007. Once on station the acoustic release was interrogated to confirm operation and that the mooring remained on the deployed location. Following position verification, a release command was sent and the acoustic release parted from the recovery buoy and rope. Once the recovery buoy reaches the water surface the vessel is maneuvered into position for the recovery of the mount.

Interrogation of the acoustic release at site 1 revealed the bottom mount had moved approximately 87 m south of the deployment position. Repeated attempts to send the recovery buoy to the water surface failed although the acoustic release command was accepted and verified by the acoustic release located on the bottom mount. Attempts were made to drag and catch the mount using heavy line and grapple hooks without success. A second recovery trip using commercial divers was also unsuccessful although the acoustic release on the bottom mount could still be ranged upon. A strong current and lowered visibility contributed to the failed recovery attempt. A third and final recovery trip was made on 19 September 2007 using EHI divers. The mount was successfully recovered but found to be flipped over, and the buoy line cut with no recovery buoy attached. A brief review of the data showed it had flipped over on July 1, just the day prior to the original service trip on July 2.

Interrogation of the acoustic release at site 2 revealed the bottom mount had moved approximately 900 m south of the deployment position. The service vessel repositioned for recovery at the new location and the recovery buoy came to the surface following transmit of the release codes to the acoustic release. The recovered location was to be the new location for deployment 2. However, because of the movement of the mount and concerns for recovering the mount following the next deployment, it was elected to redeploy the mount in the same location as deployment 1. Prior to deployment additional weight was added to the mount to help deter movement again. Recovery of site 2 occurred 2 August 2007 without incident. The mount remained at the deployment site for the entire measurement period.

Recovery of the mount at site 3 occurred without incident for both deployments. The first deployment was recovered on 2 July. The second deployment was recovered on 2 August.

3.5 Data Processing and QA/QC

The data has undergone data processing using EHI standard routines. To begin processing, the data were referenced relative to Mean Lower Low Water (MLLW). Draft data plots were generated and all obvious erroneous data points were flagged and removed from the final data files (replaced with 999 place holders). All out of water measurements were deleted from the processed data files and plots.

For periods in the records when the mount moved a noticeable distance, adjustments were made to the record or the record was split and treated as separate deployments. The two cases where this occurred were site 1 and the first deployment for site 2. During the first part of deployment at site 1 the mount was moved upslope about 3 meters on 14 June 2007. The current record was split and each half was adjusted to MLLW. The two halves were then recombined and offset so MLLW of each bin matched depth wise. When viewed as an entire record the result is nearly seamless. Statistics (percent occurrence) was then run for the entire record.

Data for site 2 deployment 1 were split into two current records. The mount moved too far (900 m) to consider the record as a whole. Fortunately, the mount remained in the original deployment location for 15 days before migrating south and in approximately 4 meters shallower depth and collected another 15 days of data. Since each site collected over 14 days of data (half a tidal month) they were considered two different records for two different sites.

Appendix B contains data plots and tables for the new current records. Color contours of current speed versus depth and time, and current direction versus depth and time for the deployment periods are shown first. Current speed is in cm/s. Current direction is in degrees True. Conversion of cm/s to knots: 51.4 cm/s = 1 knot. Depth is with reference to MLLW.

The second set of color contours are measures of data quality and depend on the type (brand) of ADCP deployed. For sites 1 and 2, a Sontek ADP was used to measure currents. The color contours for this meter include signal to noise (dB) and amplitude (counts) for each of the three transducer beams. For site 3 a RD Instruments ADCP was used. The color contours include current vertical velocity, error velocity, correlation, and intensity versus depth and time. The bottom panel is average vertical (water column average) velocity versus depth and time. Velocities are in cm/s. Correlation and intensity are in counts.

Time history plots of water level (pressure sensor in m), temperature (degrees Celsius), pitch and roll of the tilt sensor (degrees), and heading from the compass (degrees True).

Time series vector plots of the measured currents at selected depths. For readability, each deployment at six depths (maximum) is plotted per page. For Appendix B, data are plotted at 2m increments for site 1 and 5m increments for sites 2 and 3. In these plots, the length of the vector is equal to the speed of the current according to the speed scale (in cm/s). The direction of the vector equates to the current direction, with the current moving from the centerline toward the tip of the vector. North is towards the top of the paper, east to the right, south to the bottom, and west to the left. The red line is the speed value overlaid on the vector plots for visual reference.

For each depth that a time series vector plot is provided, a table showing the percent of the measurements within 10 cm/s speed bins, and 20-degree direction bins, is provided. Directions are degrees True.

3.6 Data Quality and Quantity

The data presented in Appendix B is of high quality. The only missing data occurred during the second deployment period at site 1 when the mount tipped over and the data was compromised. The meter contains good data from 30 May through the afternoon of 1 July. The unit moved on the bottom some during the first half of June, as noted in the heading, pitch and roll record, but there was no significant affect to the measurements. There are a few measurements on 14 June when the pitch and roll change by approximately 8 degrees and 25 degrees, respectively and heading changed by about 100 degrees. Data during this 45 minute period has been eliminated from the processed current record.

The mount deployed at site 2 moved 900 m half way through the first deployment. Since fourteen days of data (half a tidal month) was collected at both the original and final resting point, the record was split into two current records (2a and 2b). Plots and statistics were run for each data set. Deployment 2 for site 2 was deployed at the original deployment location for deployment 1. With extra added weight to the mount it remained in place for the entire deployment. To be consistent with the labeling for deployment 1, this record is labeled site 2a.

Both deployments for site 3 remained stable through the deployments. There is some settling of the mount the first day of deployment 1 (see heading, pitch and roll record) but the adjustments were less than 4 degrees for all parameters and therefore had no affect on the data.

4.0 MEASUREMENT RESULTS

4.1 Spatial Variation

Spatial variations are evident both along channel and across channel. Moving from north to south through the Narrows the current speed increases as well as changes direction to align with the bends in the channel. Starting at TP4, just north of the entrance to the Narrows, the current is predominantly to the NW. This area is directly influenced by the clockwise rotation of the currents around Vashon Island. There is a cluster of sites (TP5-TP8 and the new TP3) at the north section of the Narrows. Speeds at these sites have increased over those measured at site TP4 and the current directions align with the NW-SE orientation of the channel. Also clear is a shift to a predominantly southward flood current. The flood (southward) current is 2 to 2.5 times stronger than the ebb (northward) current. Moving southward to sites TP1 and TP2a the current flow shows a change in direction to reflect the bend in the channel. The ebb current is N to NE and the flood current is S to SW. Stations at the south end of the Narrows, TP2b and TP9-TP10, show a definite NE ebb current and SW flood current. In addition, the current strength for both tides is approximately equal.

Cross channel variability can be viewed at sites TP1-TP2a. In the upper water column the current directs change on the ebb tide from SSW to SSE moving from site TP1 to site TP2a. The near bottom currents at both sites appear to be the same, N on ebb and SSW on flood. Another feature of cross channel variation is the difference of the daily maximum ebb and flood currents. At site TP1 the flood current has higher speed compared to the ebb current. At site TP2a the max ebb and flood currents closely match in speed.

4.2 Time Variation

The most direct comparison between seasons is viewing the historical data for the northern sites (TP5-TP8). Sites TP6 and TP8 were measured during the spring (February to April) while site TP5 and TP7 were measured during fall months (September to November). In viewing the percent occurrence tables there does not appear to be any seasonal change at this location in the Narrows. All sites for all months show the flow is 130°-170° (southeastward) for 45% - 70% of the record and flows 310°-350° (northwestward) for 20% - 30% of the record.

4.3 Percent of Time of Larger Currents

While there are dominant directions to the flood and ebb currents off Point Evans, to determine the total power available in the water to drive a turbine device, the most important factor is the percent of time the current stays in excess of various speeds. This assumes that any tidal current turbine device will have the ability to either align itself with the current flow, or be able to handle some directional variation in the current without significant reduction of its capabilities.

The percent of time of various current speeds exist at the measurement sites regardless of the current direction are presented in Percent Occurrence Summary Tables at the end of each Appendix (A for historical measurements and B for new measurements). Figure 4 shows a visual representation of these tables. Surface currents (depths below 0 MLLW) have the highest percentages. What is striking from the >50 cm/s plot is that the majority of the data records have currents in excess of approximately 1 knot over 50% of the time through the water column. Sites TP1, TP2 (both a and b), and TP9 consistently have the highest percentages progressing through the speed bands. This summary shows that currents in excess of 150 cm/s (~ 3 knots) exist only 30-40 % of the time at measurement sites TP1 and TP2 near the surface and decrease almost linearly with depth. Site TP3 has currents in excess of 150 cm/s only 15% of the time although these speeds occur through most of the water column.

4.4 Dominant Direction

The vector plots and percent occurrence tables reveal that the dominant current direction is different for the northern part of the Narrows compared to the southern part. In the northern part (sites TP5-TP2a) the dominant flow is on the flood tide (southerly). In the southern part of the Narrows (sites TP2b and TP9-TP10) the flow is fairly evening split between the flood and ebb tidal currents.

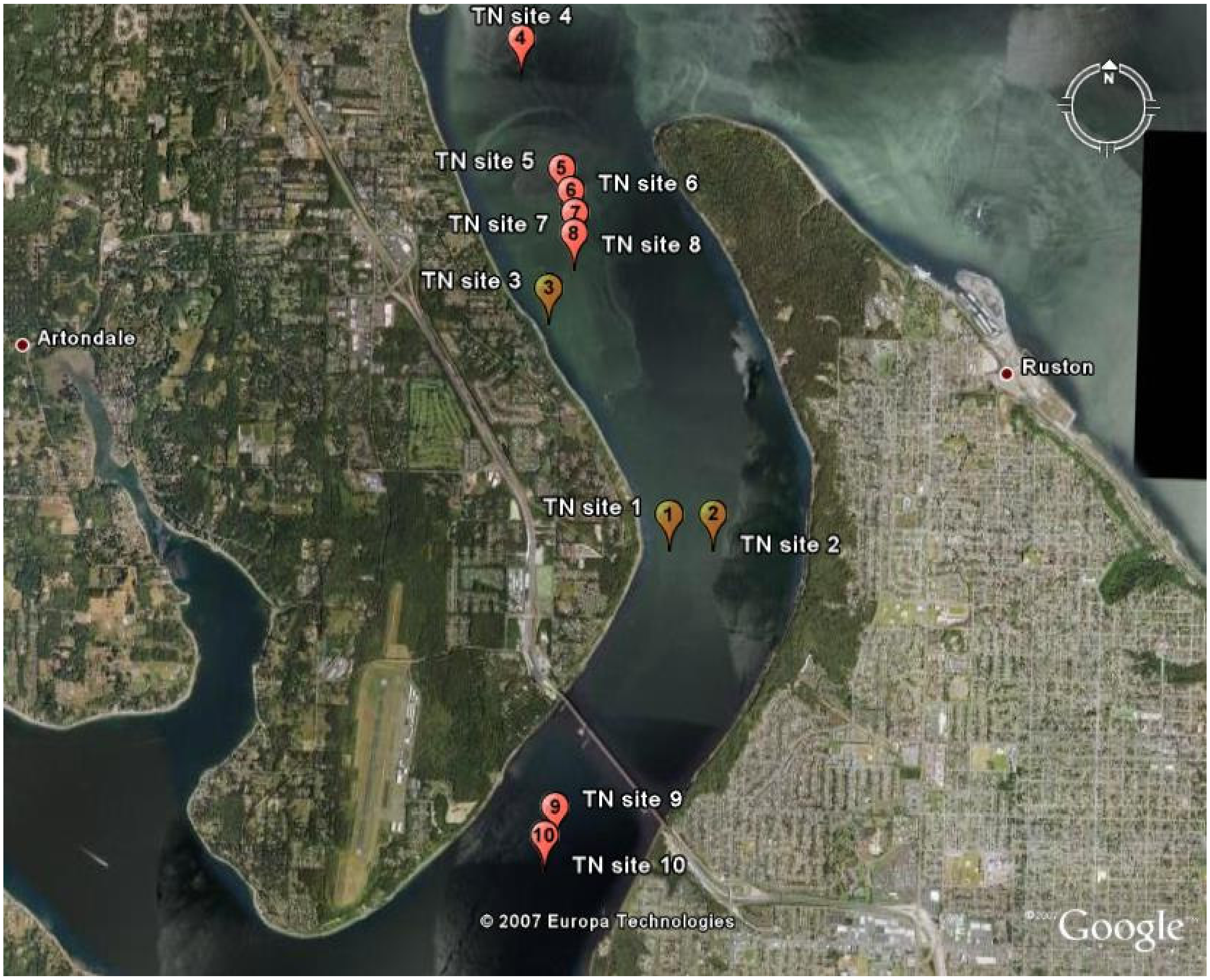
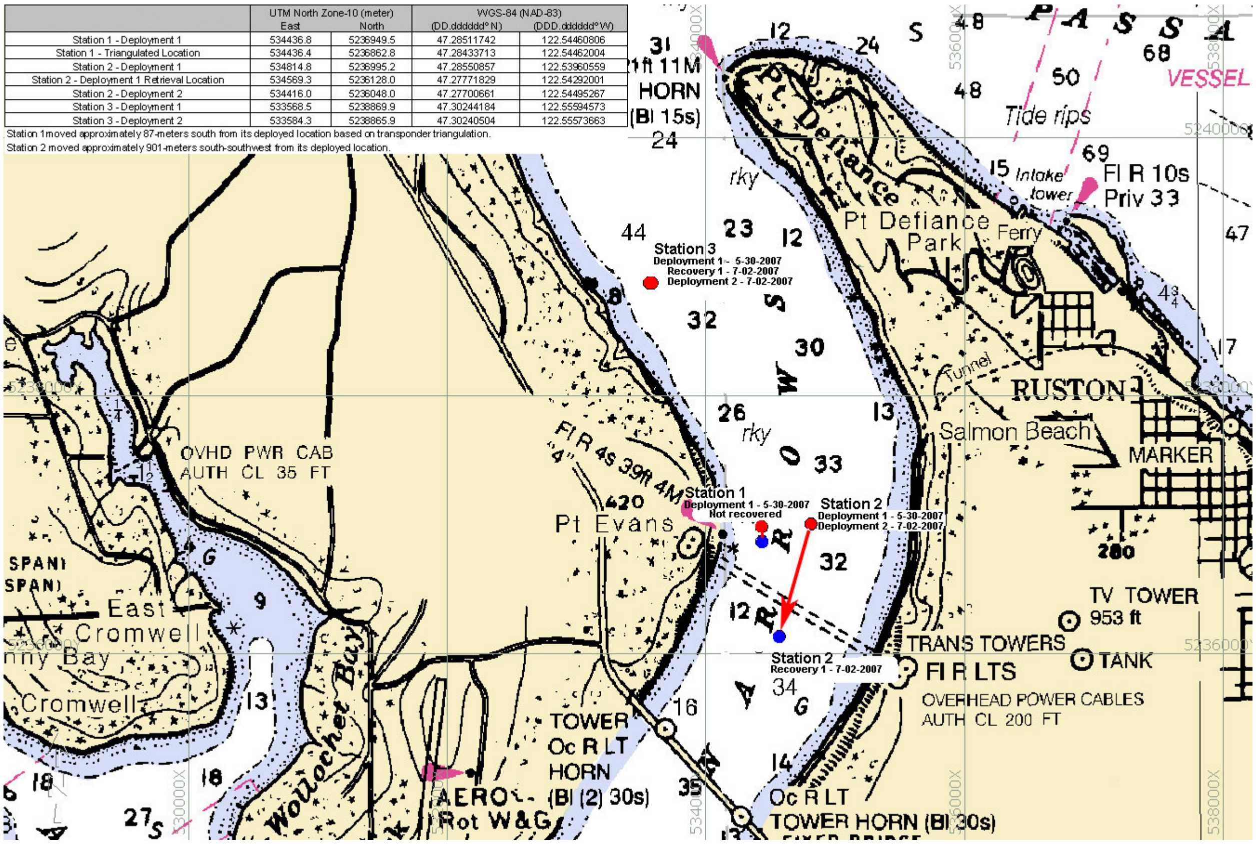


Figure 1 Location of current mooring sites used for this report.



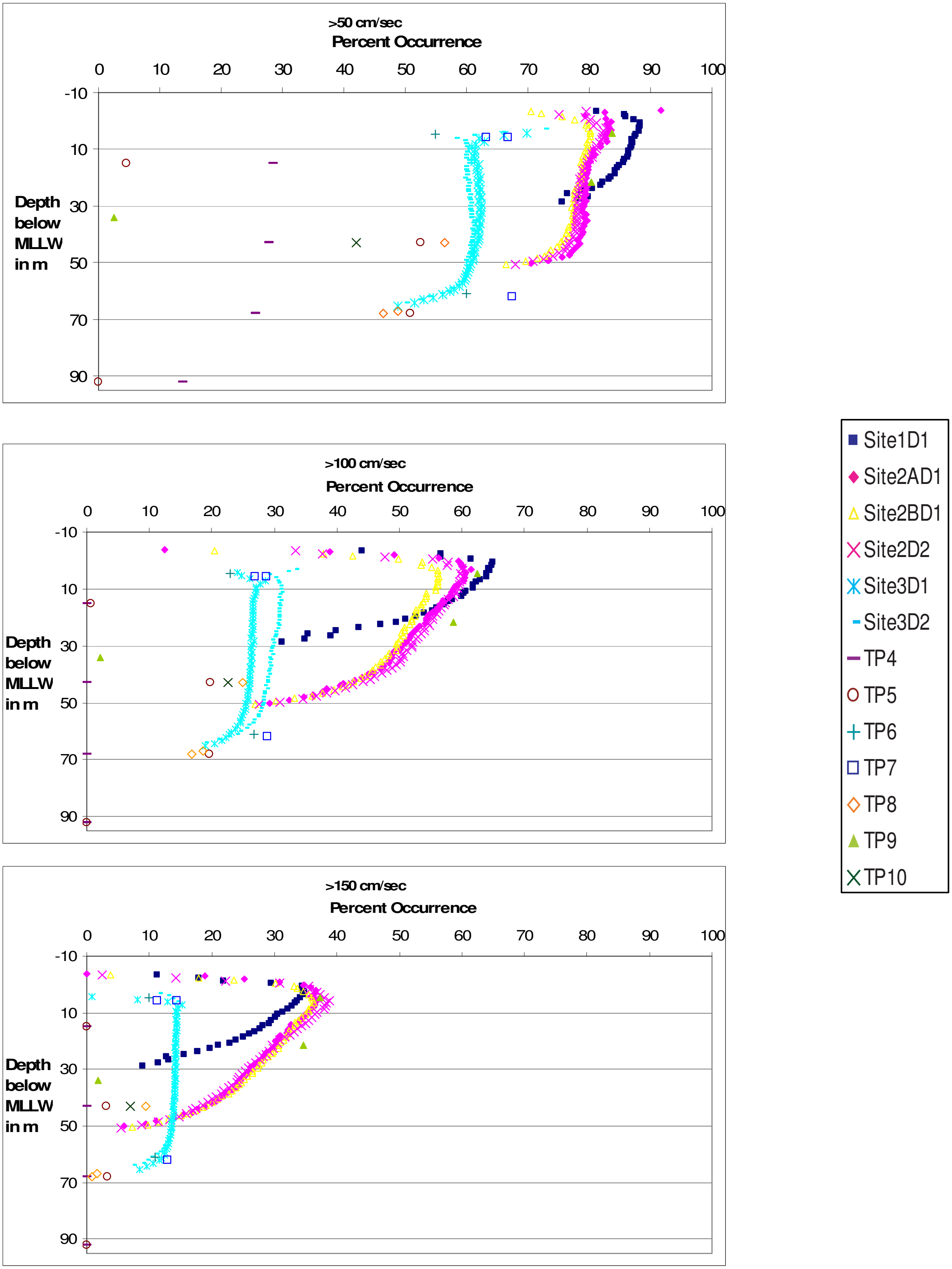
	UTM North Zone-10 (meter) East	North	WGS-84 (NAD-83) (DD.dddddd° N)	(DDD.dddddd° W)
Station 1 - Deployment 1	534436.8	5236949.5	47.28511742	122.54460806
Station 1 - Triangulated Location	534436.4	5236862.8	47.28433713	122.54462004
Station 2 - Deployment 1	534814.8	5236995.2	47.28550857	122.53960559
Station 2 - Deployment 1 Retrieval Location	534569.3	5236128.0	47.27771829	122.54292001
Station 2 - Deployment 2	534416.0	5236048.0	47.27700661	122.54495267
Station 3 - Deployment 1	533568.5	5238869.9	47.30244184	122.55594573
Station 3 - Deployment 2	533584.3	5238865.9	47.30240504	122.55573663

Station 1 moved approximately 87-meters south from its deployed location based on transponder triangulation.
Station 2 moved approximately 901-meters south-southwest from its deployed location.

Figure 2 Locations of new current records. Red dot indicates deployment 1 location and blue dot indicates deployment 2 locations. The red arrow shows the distance traveled by the site 2 mount during the first deployment.

Figure 3. Bottom mounts.

Figure 4 Percent time for increasing current speeds.


>50 cm/sec
Percent Occurrence
Depth below MLLW in m
0 10 20 30 40 50 60 70 80 90 100
-10 10 30 50 70 90
>100 cm/sec
Percent Occurrence
Depth below MLLW in m
>150 cm/sec
Percent Occurrence
Depth below MLLW in m
Site1D1
Site2AD1
Site2BD1
Site2D2
Site3D1
Site3D2
TP4
TP5
TP6
TP7
TP8
TP9
TP10

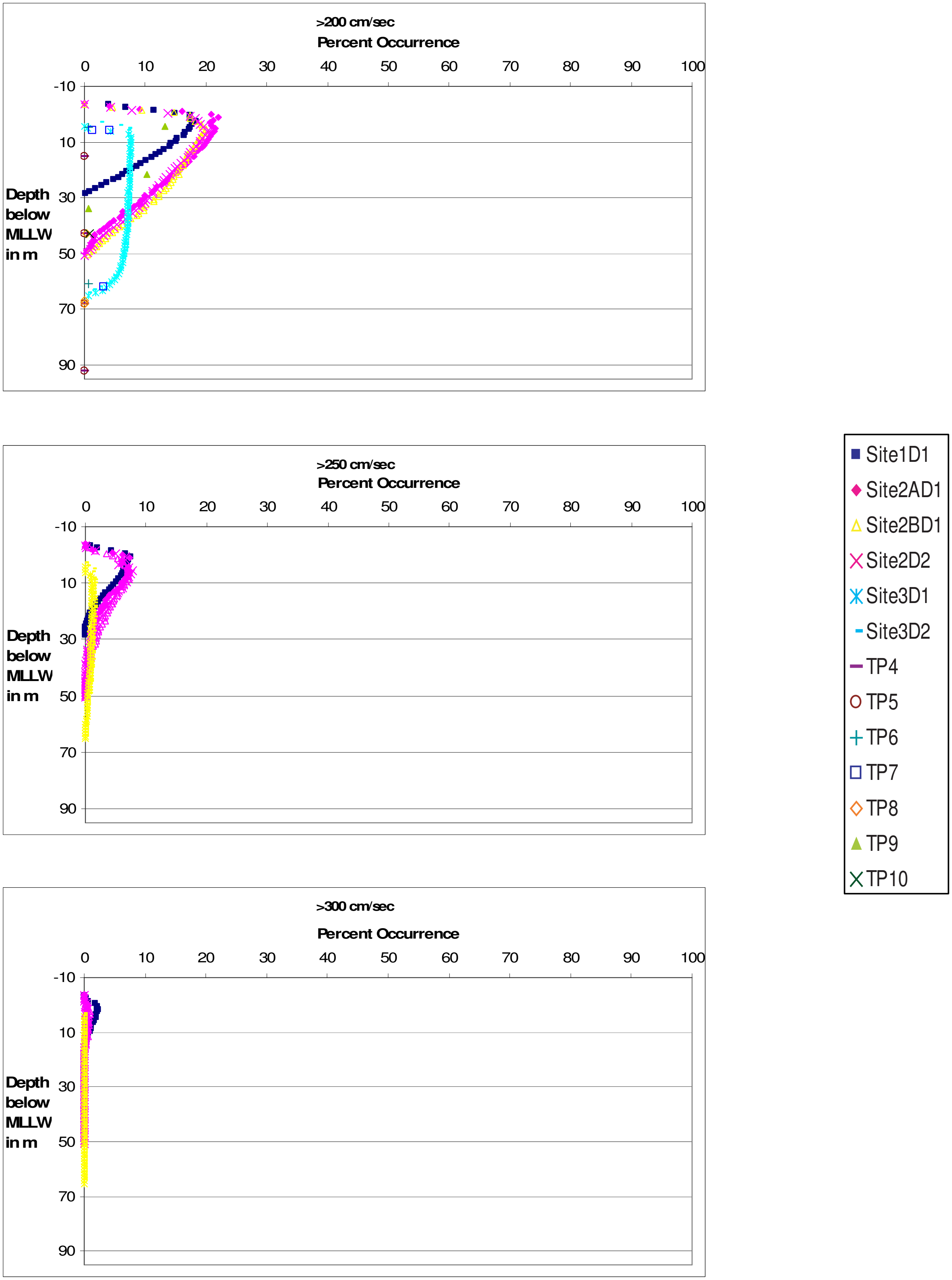

>200 cm/sec
Percent Occurrence
Depth below MLLW in m
>250 cm/sec
Percent Occurrence
Depth below MLLW in m
>300 cm/sec
Percent Occurrence
Depth below MLLW in m
Site1D1
Site2AD1
Site2BD1
Site2D2
Site3D1
Site3D2
TP4
TP5
TP6
TP7
TP8
TP9
TP10

Table 1 Historical Current Records

TP Site ID	Latitude (N)	Longitude (W)	Bottom Depth (Meters)	Meter Depth (Meters)	Dates of Observations Begin	Dates of Observations End	Record Length (Days)
TP 4	47° 19.3	122° 33.8		15.0	02/24/1977	03/28/1977	32.6
TP 4				43.0	02/24/1977	03/28/1977	32.5
TP 4				68.0	02/24/1977	03/28/1977	32.6
TP 4				92.0	02/24/1977	03/28/1977	32.6
TP 5	47° 18.7	122° 35.28		15.0	09/10/1980	11/13/1980	64.4
TP 5				63.0	09/10/1980	11/13/1980	63.7
TP 5				65.0	09/10/1980	11/13/1980	64.4
TP 5				170.0	09/09/1980	10/08/1980	29.7
TP 6	47° 18.6	122° 33.42		4.6	03/08/1978	04/10/1978	33.0
TP 6				15.2	03/08/1978	04/10/1978	33.0
TP 7	47° 18.5	122° 33.42		5.8	10/17/1977	11/01/1977	15.0
TP 7				15.2	10/18/1977	11/18/1977	30.2
TP 7				5.8	11/01/1977	11/17/1977	15.2
TP 8	47° 18.4	122° 33.42		43.0	02/24/1977	03/28/1977	32.5
TP 8				67.0	02/24/1977	03/28/1977	32.5
TP 8				68.0	02/24/1977	03/28/1977	32.5
TP 9	47° 15.73	122° 33.42		4.9	03/09/1978	03/30/1978	20.1
TP 9				21.6	03/09/1978	03/29/1978	20.1
TP 9				15.2	03/09/1978	03/29/1978	20.1
TP 10	47° 15.6	122° 33.48		43.0	02/24/1977	03/28/1977	32.6

Table 2 New Current Records.

TP Site ID	Investigator Station Number	Latitude (N)	Longitude (W)	Bottom Depth (Meters)	Meter Depth (Meters)	Dates of Observations Begin	Dates of Observations End	Record Length (Days)
DEPLOYMENT 1								
TP1	EHI	47° 17.1	122° 32.7	30	30	05/30/2007	07/01/2007	31
TP2	EHI	47° 17.1	122° 32.4	49	49	05/30/2007	06/15/2007	16
TP2B	EHI					06/15/2007	07/02/2007	16
TP3B	EHI	47° 18.1	122° 33.4	65	65	05/30/2007	07/02/2007	32
DEPLOYMENT 2								
TP2	EHI	47° 17.1	122° 32.4	49	49	07/02/2007	08/02/2007	30
TP3B	EHI	47° 18.1	122° 33.4	65	65	07/02/2007	08/02/2007	30

Appendix 2: Site Assessment Bibliography

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Appendix 3: Hydroacoustic Monitoring System

Draft Proposal

Project: Tacoma Narrows Tidal Energy Feasibility Study

Task: Design and Cost of Hydroacoustic Monitoring Systems for Tidal Turbines in the Tacoma Narrows

Submitted to: Puget Sound Tidal Power, LLC, Seattle, Washington

Submitted by: BioSonics, Inc., Seattle Washington

Submission Date: November 2, 2007

Executive Summary

It is currently unknown how often large, submerged objects drift through the Tacoma Narrows. These objects may include boulders, deadhead logs, fishing nets, debris or even large marine mammals, and could potentially strike the turbines installed in the Narrows. Therefore, it is important to know how often such large objects pass through the Narrows, and at what depth, to help determine optimal turbine placement locations. BioSonics, Inc. proposes the long-term deployment of an automated, unmanned, hydroacoustic monitoring system at the study site to determine this information.

In addition to quantifying the trajectories of large objects capable of damaging turbines, a long term monitoring study will also provide a base line assessment of marine species abundance, distribution, behavior and migratory patterns in the Tacoma Narrows. This knowledge will also be crucial in determining optimal turbine placement to minimize possible negative impacts of the turbine field on animals passing through or living in the vicinity.

Once a pilot turbine or group of turbines is deployed, the hydroacoustic monitoring system could be expanded or reconfigured to monitor the specific region around the turbine with particular focus on the zones of high risk around the turbine blades, to assess the occurrence of marine species injury due to blade strikes.

BioSonics is currently working closely with Verdant Power, Devine Tarbell and Associates, and several state and federal regulatory agencies on the Roosevelt Island Tidal Energy (RITE) project in New York City's East River. The BioSonics scientific and engineering team designed, built and installed an automated hydroacoustic monitoring system at the site that provides continuous coverage of the underwater environment throughout the turbine field. The system has been in non-stop operation since the first turbines were installed in the fall of 2006. As fish and other marine life pass through the turbine field, the BioSonics monitoring system automatically tracks and documents the location and behavior of each individual relative to the zone of risk at each turbine. Advanced real time, unmanned data processing and reporting techniques developed by BioSonics provide hourly reports of aquatic species activity. The ability of the monitoring system to provide this continuous, comprehensive knowledge about the project's impact on the biological community has proven to be a critical factor in the permit approval process

The application of scientific acoustic techniques to monitor at the Tacoma Narrows is detailed in this proposal.

Introduction

The emerging hydrokinetic energy industry is experiencing significant opportunities while at the same time facing daunting challenges. Chief among the opportunities is reducing carbon-based power sources and lowering greenhouse gas production. The challenges come on all fronts. Power producers are mandated by government to achieve some percentage of renewable energy in their power production portfolios. Developers and investors are attempting to evaluate potential sites and generation technologies to make power production economically feasible. Regulators usually have sketchy or insufficient data to characterize the risk that turbines might impose on fish and other living organisms.

The Federal Energy Regulatory Commission (FERC) is designing a permitting process that integrates these concerns and streamlines the permitting process. They presented a new Pilot Permitting Process Proposal in a meeting on October 2, 2007, in Portland Oregon. In this streamlined process, they admitted that the risk of negative environmental impacts might increase due to relaxed permitting conditions, and proposed a four-factored approach to mitigate these concerns:

Reduce the permit duration to 3-5 years
Recognize a relatively small project footprint
Employ monitoring
Recognize that project might be stopped or removed if impact was high.

Tacoma Public Utility District (PUD) has entered this dynamic arena by selecting the Tacoma Narrows site as a potential candidate for hydrokinetic power production. The PUD selected Puget Sound Tidal Power LLD, a consortium of local companies involved in marine engineering, to assist in evaluating the site for hydrokinetic development. Initial hydraulic studies revealed that the power potential of the site was greater than expected, and the project is preparing to move into the second phase. A significant aspect of this next phase is to provide monitoring of the proposed site, as mentioned by FERC in their Pilot Permitting Process discussed above. Of the various monitoring methods and technologies available, it was concluded that scientific acoustic techniques provide a unique blend of attributes: cost efficiency, low operational costs, safe to use in high-velocity flow areas, non-invasive sampling, a 27 year history of fisheries monitoring for FERC re-licensing at hydroelectric dams, legally and scientifically defensible results, a high degree of automation, and over a year of monitoring experience at Verdant Power's Roosevelt Island Tidal Energy (RITE) project.

This document details a proposed plan to monitor the Tacoma Narrows site using scientific acoustic techniques. Monitoring efforts will focus on two areas. First, the monitoring will document the movement of large passively drifting objects moving through the study footprint – objects that may pose a risk to underwater turbines. Second, the monitoring will document how fish, sea birds, and marine mammals use and transit through the study site. The overall monitoring scenario for the project is discussed, followed by detailed descriptions of the proposed system components and installation. Deliverables from the acoustic system are described in detail. Appendices provide additional details on the host of support functions required to prepare and install the acoustic systems, and also a detailed description of acoustic monitoring at the RITE site.

Introduction to Acoustic Monitoring

Many agencies, scientists, and developers are unfamiliar with scientific acoustic techniques, due in part to its complexity and foreign jargon. This introduction provides a descriptive vision or 'big picture' of these techniques and how they will be used at the Tacoma Narrows hydrokinetic energy site.

A scientific echo sounder is designed to transmit a known amount of sound energy, and receive echoes from the surface and bottom boundaries, as well as from fish, birds, marine mammals, passively drifting objects, and any other target that reflects sound pressure. The sound pressure levels are modified by transit through the water – the scientific echo sounder amplifies the returning echoes to precisely compensate for these effects. The echo sounder outputs displays in real time, as well as writing digital data files to a computer hard drive. Figure 1 shows an echogram display, which is a time series of data with range on the Y-Axis and time on the X-Axis. This display represents about 3 minutes of data. Figure 2 shows detection of an inanimate object, which begins to move some time after detection. This object is the nose of the turbine that has yawed into position by the current, and the blades have begun to rotate after current velocities have become high enough. A host of published literature assists the acoustic scientist in interpreting the data files and converting reflected echoes into counts and size estimates.

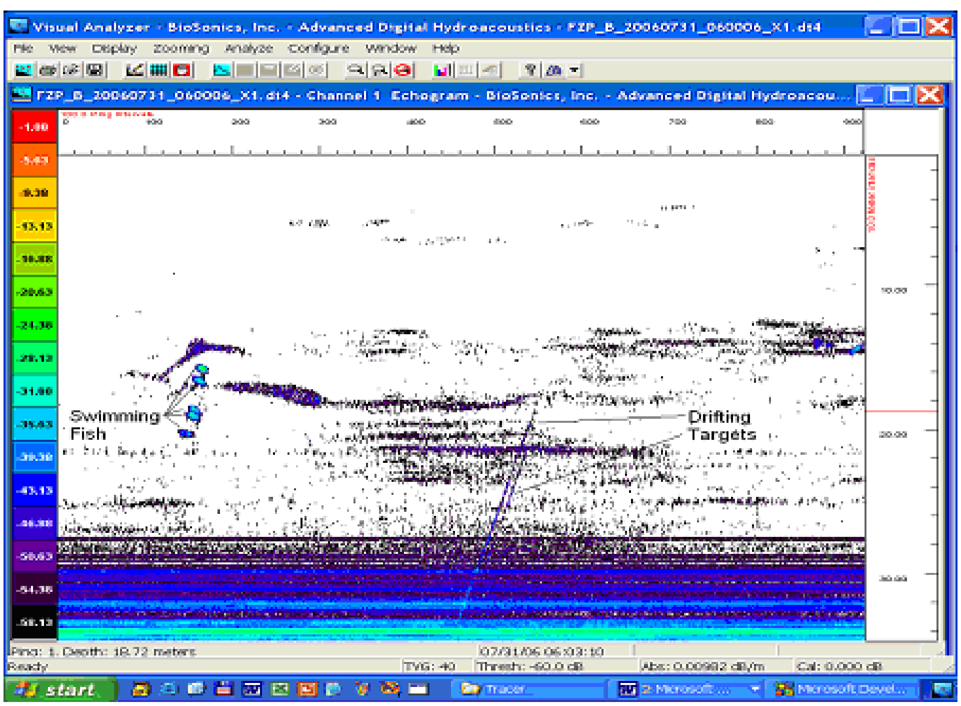


Figure 1. Echogram Display Showing Fish and Drifting Objects

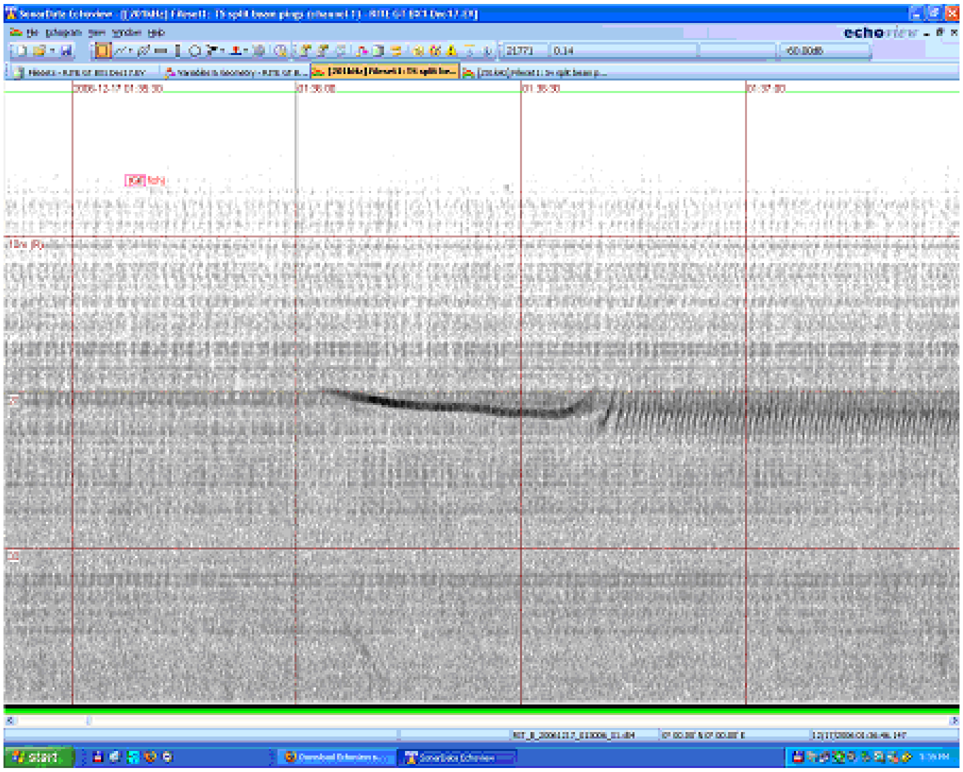


Figure 2. Echogram Showing Inanimate Object

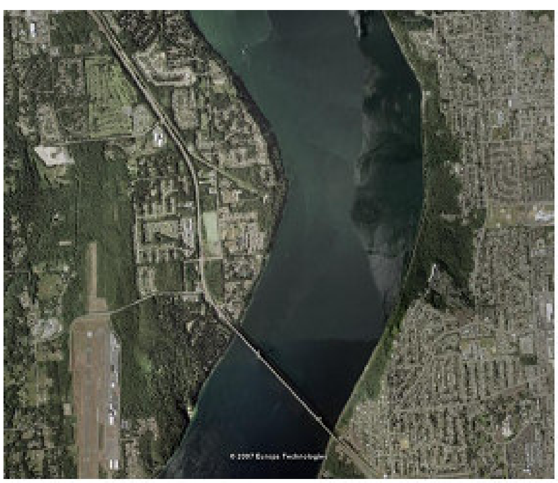


Figure 3. Satellite View, Tacoma Narrows

Acoustic monitoring at the Tacoma Narrows site falls into two categories – monitoring for large Passively Drifting Objects (PDOs) that might damage turbines, and monitoring for fish and other living marine resources. These two monitoring tasks are accomplished by the same type of equipment, and at the same location. The plan view in Figure 3 shows a satellite view of the Tacoma Narrows region. Figure 4 indicates the position of the acoustic beams (in blue) transmitted horizontally out from a near-shore location to form an acoustic curtain extending from the surface to the bottom. An illustration of the vertical alignment of the acoustic beams is superimposed on a cross-sectional map of current velocity (Figure 5).

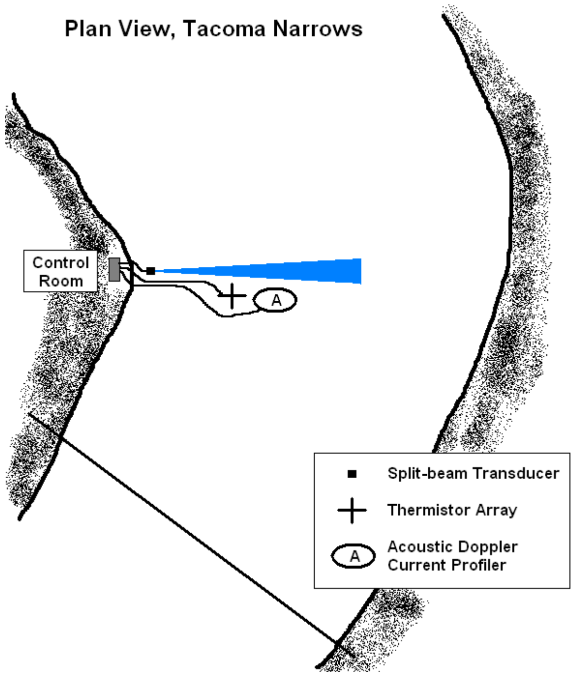


Figure 4. Plan View Illustrating Acoustic Curtain Location

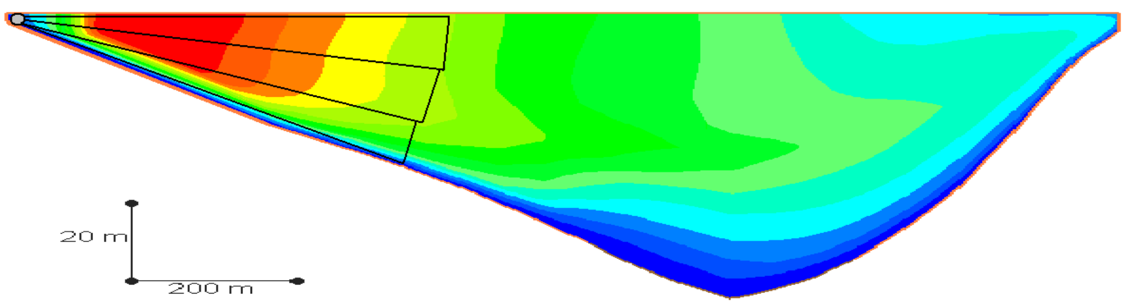


Figure 65. Vertical Alignment of Acoustic Beams

One acoustic system monitors a transducer that produces the acoustic beam adjacent to the bottom, and is used to detect Passively Drifting Objects that have a slight negative buoyancy and might damage turbines. A second acoustic system samples a transducer that is rotated between the upper and middle positions. Both systems are designed to detect targets as small as individual plankton, and as large as whales, and will be used to monitor the entire water column for fish, marine mammals, and diving birds.

If monitoring of drifting objects were the only task requested, a single acoustic system would be installed and its acoustic beam aimed as close to the bottom substrate as possible. It is believed that the frequency of large objects passing the site might be low, thus the single system would be dedicated to sampling adjacent to the bottom and not ever be rotated up into the water column. This system would also detect fish and other living resources that passed through its detection zone. If monitoring of both fish and drifting objects were requested, a second acoustic system would be added to sample one half of each hour on the beam adjacent to the water surface, and the other half of each hour at the middle position. The presence of the second system allows the first system to stay dedicated to the near-bottom orientation. This spatial/temporal sub-sampling provides a valuable estimate of how living resources use the upper two-thirds of the water column, while minimizing the project costs by eliminating a third system. In the event of a request to sample fish and other living resources only, the proposed system would be rotated through the three vertical orientations shown in Figure 5, providing 20 minutes each hour at each location. These three sampling options are reflected in the creation of three separate budgets.

The acoustic signals detected within this curtain are processed in near-real time by analytical software. Automated software creates hourly reports describing the direction of travel, and the spatial and size distributions of targets passing through the curtain. A daily report summarizing these observations is generated and automatically sent via email to project team members on a subscription list.

Acoustic monitoring is a technique in which the effort and cost are front-loaded, and the operational costs are very low. The details associated with specific tasks are discussed in the following sections.

Definition of Tasks

The design, fabrication, installation, and programming of the acoustic monitoring system represent many tasks. Some of these will be completed by BioSonics, others by coalition team members with strengths and skills more suited to specific tasks. For tasks that will be completed by groups other than BioSonics, we describe the nature of the task and provide suggestions to facilitate the planning, designs, and budgeting by other groups. Specifics of each task will be finalized during the planning stages in meetings and discussions between teams.

Shore Side Infrastructure (Completed by Coalition Member)

The primary need on shore is for an environmentally controlled housing for the acoustic equipment, reliable 120 VAC power, high-speed Internet connection, and security from vandalism. We also require some protection for signal cables emerging from the water line and traveling to the environmental enclosure.

BioSonics suggests that the team follow the example of Verdant Power at the RITE project site, and install an enclosure similar to a shipping container. Most electronic equipment could be rack-mounted inside this structure. This space could be made secure from vandalism, and could be wired to connect future test generators to the grid. If possible, the container would be installed on the west shore above the study site, providing the shortest routing of power and signal cabling. We suggest installing a web cam aimed East over the study footprint, and a second aimed inside the container for security purposes. This container would become the area of congregation and focus for project personnel, visitors from other tidal energy projects, government officials, and the media.

To protect cabling that comes from the water to the enclosure, we suggest either of two strategies. First, a trench could be dug from the shore to the container to allow cables to be buried. Second, cables could be routed through some type of conduit from water's edge to the container. Based on preliminary designs, BioSonics plans to have a single fiber optic / power cable coming from the underwater nodes to the enclosure. Additional cables might be present if other underwater sensors are installed.

Acoustic System Components (BioSonics)

In Figure 6, the block diagram of the proposed acoustic systems for detecting fish and drifting objects illustrates the underwater components.

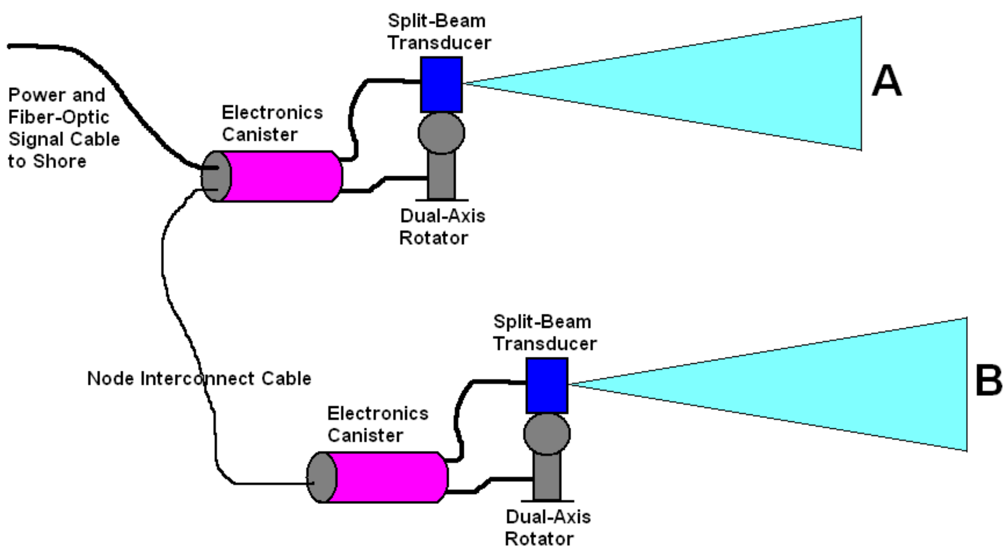


Figure 69. Block Diagram of Underwater Acoustic Components

The systems for monitoring Passively Drifting Objects (PDOs) and living resources are essentially identical. The PDO detection system is proposed to operate at 200 kHz, while the other system will operate at 120 kHz to minimize reflections from surface turbulence. Both transducers are split-beam, a technique that allows direct estimation of the position of a target inside the acoustic beam. Both are mounted on remote-control programmable dual axis rotators. The beam labeled as 'B' will be aimed as close as possible to the bottom substrate to detect PDOs. The beam labeled 'A' will be sampled within each hour at two positions. In the first position, the beam will be rotated as close to the surface boundary as possible while minimizing interference. After collecting a sample of data, the beam will then be rotated down into the mid-water position. Based on bathymetry information, these three sampling locations should provide complete water column coverage.

A BioSonics DT-X scientific echo sounder will be attached to each of the split-beam transducers. These echo sounders will be installed in pressure canisters and located inside the transducer mount structure. One of the canisters will also contain an Ethernet router or hub. Power will be supplied from shore, and signals from both canisters will be sent back to shore through the fiber-optic cable.

The fiber-optic cable will be routed into the Shore side enclosure to a rack-mounted computer. This computer will control the functions of the echo sounder and will store the acoustic signals onto mirrored RAID drives. Processing software and report-generating software will run on this computer and be programmed to transmit monitoring results to selected recipients on a daily basis. Once programmed, the data collection, analysis, and reporting are completely automatic.

Design and Fabrication of Transducer Mounts (Completed by Coalition Member)

Transducer mounts must provide a protective housing for the electronics canister, the rotator, and the transducer and cabling. The housings should be designed to minimize snagging of hooks or nets. The housing must be heavy enough to not move in the strong current, or its design must allow it to be directly anchored to the bottom substrate. The drawing in Figure 7 suggests one type of mount design.

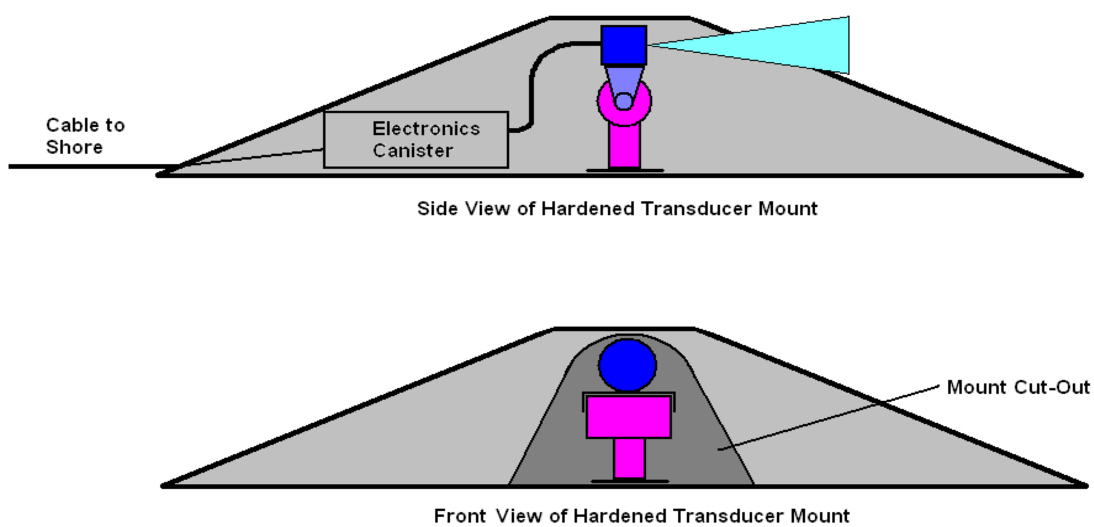


Figure 70. Proposed Trawl-Resistant Transducer Mount

This design represents a steel structure shaped like a Limpet shell, and has a cut-out for the transducer to transmit the sound beam through. This design will be finalized after consultation with team members.

Transducer Mount Installation (Completed by Coalition Member)

Selection of the specific installation site will be based on discussions with Tacoma Power and with Coalition members. Although the installation provider will determine the specifics of the installation methods, we anticipate that the provider will follow steps similar to the following. All electronic and acoustic components will be installed in each mount, along with the cable and protective conduit that will eventually be routed back to shore. Three eyebolts will be screwed into the top of the mount, a lifting bridle attached, and the mount lifted up via boat winch and crane. The first mount would be lowered to the desired installation spot, where the precise bottom depth and latitude/longitude would be recorded. The heading of the mount could be stabilized by attaching a temporary light rope to the shoreward side and maintaining a slight pressure from a second boat (it is necessary that the cutout is facing directly offshore). Once the mount reaches the bottom, a diver examines it and attaches it to the bottom if necessary. The Heading/Pitch/Roll sensor inside each split-beam transducer records the precise orientation of the mount. The tensioning rope is removed, and the inter-connect cable tied off to a floating buoy. The second mount would be assembled on deck, and the inter-connect cable retrieved from the buoy and attached. Depending on the length of time required to lower and secure the first mount, the second mount might have to be installed during the next slack tide. This second mount would be lowered into position, and secured to the bottom substrate. The fiber optic cable would be carefully routed back to a selected point on the beach. The diver would complete the cable routing and secure cable or conduit to the bottom. The entire installation process must be carefully choreographed as the slack current window is likely to be of short duration and the amount of time the diver can work would therefore be limited. It may be possible to install both transducers in a single mount if the specific bathymetry at the installation point is suitable.

Installation of Other Sensors (Completed by Coalition Member)

If we continue to follow the Verdant Power example, we suggest that the project benefits by installing several other sensors. We suggest that an Acoustic Doppler Current Profiler (ADCP) be installed on the sea floor in the approximate vicinity of the turbines. The ADCP signal cable would then be routed back to shore and into the enclosure. This sensor would provide flow velocity data in real time, which would be made available to the acoustic analysis software to incorporate into the analysis. It would be critical to know if a large target detected by the acoustic system were passively drifting or if it were swimming against the current.

We also suggest that a streaming CTD be installed near or on the transducer mounts to provide continuous salinity and temperature measurements to the project in real time. The acoustic system would tap into this data stream and continually re-program the echo sounders to compensate for changes in salinity and temperature.

Finally, it would be beneficial to have a weather station attached to the environmental enclosure, or to have access via Internet to a local station. Wind speed and direction would be obtained from this sensor.

Acoustic Data Collection, Analysis and Reporting (BioSonics)

Following installation of the two transducer mounts and routing of cables back to the instrument enclosure, the transducer aims will be established, and the rotators programmed to implement those aims. The data collection parameters will be programmed into the echo sounders, as well as file archiving instructions. The data analysis parameters will be programmed into software, and the report subscription list prepared. The acoustic system will be turned on, and the entire monitoring process is automated from this point on. BioSonics personnel will check the system operation via Internet each work day to insure proper operation. We will also install several "Watchdog Programs" that look for malfunctions in the data collection and processing, and send an alert email back to our engineering department. These watchdog routines can reset and restart data collection and analysis processes under most conditions.

We propose to analyze the data in a series of range and depth cells and report the number of fish or objects passing through each cell per hour (Figure 8).

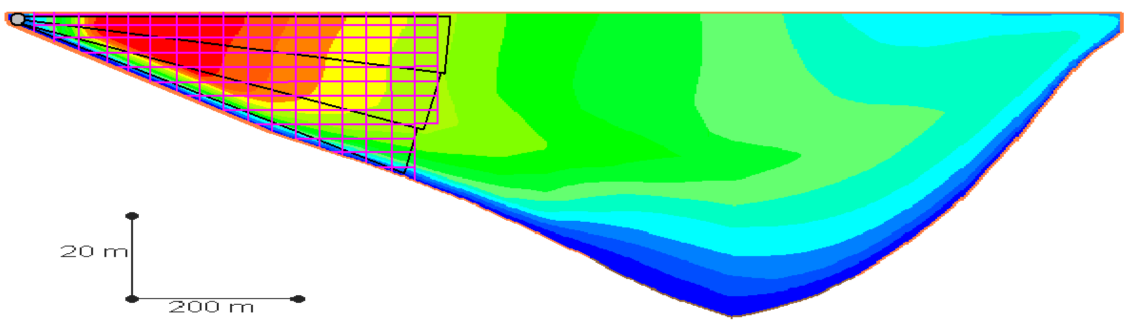


Figure 71. Hypothetical Analysis Grid for Acoustic Deliverables

The grid shown in this figure represents a hypothetical framework in which hourly results might be calculated. The mean acoustic size (Target Strength) in each cell would also be reported. After a turbine is installed, a circular cell representing the disk of rotation would be defined, and numbers of fish passing through that disk would be reported. An ALERT condition could be transmitted if fish numbers aligned with this disk of rotation surpassed a predetermined threshold.

The hourly and daily summary reports are considered provisional as they are generated by automated software. A sample of data files will be evaluated and ground-truthed on a periodic basis. Ground-truthing of acoustic data is a process in which we compare results of automated and manual processing.

New Capabilities (Undefined Task)

Receiving acoustic detection data in real time provides a unique opportunity. The FERC Pilot Permitting meeting in Portland introduced several strategies to address environmental impact, the last of which was to stop or remove a project. If turbine developers build in a braking mechanism and a communication link into their units, the acoustic system can recognize predetermined risk events and send a shutdown command to a turbine. This ability to install a "smart turbine" should provide some relief to investors who fear that investment in a project may be lost if an environmental impact is detected that required project removal. If the impact is temporal, and if turbine shutdown can be biologically triggered, the project will automatically adapt to and work around environmental risks. This task is not proposed at present, but is mentioned to encourage turbine vendors to build these control capabilities into their units.

Budgets

In the preceding text, we have suggested that other team members are better suited to complete some of the tasks related to or supporting the acoustic monitoring. Additionally, we have described a shore side structure that provides a high speed Internet connection. The Internet connection allows remote access to the project, minimizing travel costs. No exact monitoring locations or turbine deployment technologies have been specified, therefore the proposed monitoring plans, transducer mount designs, and installation labor levels may require modification after final designs and locations are determined.

Separate budgets have been requested for the monitoring of passively drifting objects and of living organisms. Three budgets are presented (Figures 9 - 11). The first budget is for a study designed to detect fish, marine mammals, and other living organisms. The second budget is for a study designed to monitor passively drifting objects. The third budget details the costs for monitoring both drifting objects and living organisms simultaneously.

All budgets are divided into three phases – a project planning phase, a system installation phase, and a monitoring phase. As the monitoring duration is undefined at present, the third phase costs are presented on a monthly basis. A monitoring duration of 12 months is assumed in the three budget summaries.

The timing of the budget is related to the schedules shown in the Gantt chart, and pivots around a start date represented by an official written Notice to Proceed.

BioSonics, Inc. Budget #1 1-Nov-2007

Cost Estimate: *Acoustic Monitoring of Living Targets at the Tacoma Narrows Hydrokinetic Project*

Phase 1: Planning and Pre-deployment

Labor		Rate	Quantity/Hours	Amount
			Hours	*Amount*
	Senior Research Scientist		40	$6,000
	Engineer		12	$1,800
	Subtotal, Phase 1:			**$7,800**

Phase 2: Project Deployment

		Rate	Quantity/Hours	Amount
Labor			*Hours*	*Amount*
	Senior Research Scientist		50	$7,500
	Senior Scientist		16	$2,112
	Engineer		50	$7,500
	Field Technician		50	$4,250
Travel		*Rate*	*Quantity*	*Amount*
	Vehicle Rental	100	5	$500
	Boat Rental	800	5	$4,000
	Lodging	150	15	$2,250
	Per Diem	50	15	$750
	Subtotal, Phase 2:			**$28,862**

Phase 3: Project Monitoring - Monthly Cost Proposal

		Rate	Quantity/Hours	Amount
Labor			*Hours*	*Amount*
	Senior Research Scientist		20	$3,000
	Senior Scientist		20	$2,640
	Staff Scientist		20	$3,000
	Engineer		20	$1,700
Travel		*Rate*	*Quantity*	*Amount*
	Vehicle Rental	100	1	$100
	Boat Rental	800	1	$800
	Lodging	150	1	$150
	Per Diem	50	1	$50
	Subtotal, Phase 3:			**$11,440**

Summary

Project Total, Assuming a 12-month Monitoring Period

Phase 1 - Project Preparation	$7,800.00
Phase 2 - Project Deployment	$28,862.00
Phase 3 - Project Monitoring, 1 year	$137,280.00
Equipment Lease	$89,133.00
Project Total:	**$263,075.00**

Figure 72. Estimated Budget for Monitoring Living Resources

BioSonics, Inc. Budget #2					1-Nov-2007
Cost Estimate:		*Acoustic Monitoring of Inanimate Targets at the Tacoma Narrows Hydrokinetic Project*			
Phase 1: Planning and Pre-deployment					
Labor				*Hours*	*Amount*
	Senior Research Scientist			40	$6,000
	Engineer			12	$1,800
		Subtotal, Phase 1:			**$7,800**
Phase 2: Project Deployment					
Labor				*Hours*	*Amount*
	Senior Research Scientist			50	$7,500
	Senior Scientist			16	$2,112
	Engineer			50	$7,500
	Field Technician			50	$4,250
Travel			*Rate*	*Quantity*	*Amount*
	Vehicle Rental		100	5	$500
	Boat Rental		800	5	$4,000
	Lodging		150	15	$2,250
	Per Diem		50	15	$750
		Subtotal, Phase 2:			**$28,862**
Phase 3: Project Monitoring - Monthly Cost Proposal					
Labor				*Hours*	*Amount*
	Senior Research Scientist			20	$3,000
	Senior Scientist			20	$2,640
	Staff Scientist			20	$3,000
	Engineer			20	$1,700
Travel			*Rate*	*Quantity*	*Amount*
	Vehicle Rental		100	1	$100
	Boat Rental		800	1	$800
	Lodging		150	1	$150
	Per Diem		50	1	$50
		Subtotal, Phase 3:			**$11,440**
Summary					
Project Total, Assuming a 12-month Monitoring Period					
Phase 1 - Project Preparation					$7,800.00
Phase 2 - Project Deployment					$28,862.00
Phase 3 - Project Monitoring, 1 year					$137,280.00
Equipment Lease					$84,555.00
		Project Total:			**$258,497.00**

Figure 10. Estimated Budget for Monitoring Drifting Objects

BioSonics, Inc. Budget #3					1-Nov-2007
Cost Estimate:		*Acoustic Monitoring of Inanimate Targets and Living Targets at the Tacoma Narrows*			
Phase 1: Planning and Pre-deployment					
Labor				*Hours*	*Amount*
	Senior Research Scientist			48	$7,200
	Engineer			24	$3,600
		Subtotal, Phase 1:			**$10,800**
Phase 2: Project Deployment					
Labor				*Hours*	*Amount*
	Senior Research Scientist			50	$7,500
	Senior Scientist			16	$2,112
	Engineer			50	$7,500
	Field Technician			50	$4,250
Travel			*Rate*	*Quantity*	*Amount*
	Vehicle Rental		100	5	$500
	Boat Rental		800	5	$4,000
	Lodging		150	15	$2,250
	Per Diem		50	15	$750
		Subtotal, Phase 2:			**$28,862**
Phase 3: Project Monitoring - Monthly Cost Proposal					
Labor				*Hours*	*Amount*
	Senior Research Scientist			20	$3,000
	Senior Scientist			20	$2,640
	Staff Scientist			20	$3,000
	Engineer			20	$1,700
Travel	Item		*Rate*	*Quantity*	*Amount*
	Vehicle Rental		$100	1	$100
	Boat Rental		$800	1	$800
	Lodging		$150	1	$150
	Per Diem		$50	1	$50
		Subtotal, Phase 3:			**$11,440**
Summary					
Project Total, Assuming a 12-month Monitoring Period					
Phase 1 - Project Preparation					$10,800.00
Phase 2 - Project Deployment					$28,862.00
Phase 3 - Project Monitoring, 1 year					$137,280.00
Equipment Lease					$163,417.00
		Project Total:			**$340,359.00**

Figure 73. Estimated Budget for Monitoring Living Resources and Drifting Objects

Schedule

The Gantt chart in Figure 12 offers a preliminary schedule of event associated with design and installation of one or two acoustic monitoring system. The time scale is number of days following the receipt of Notice to Proceed.

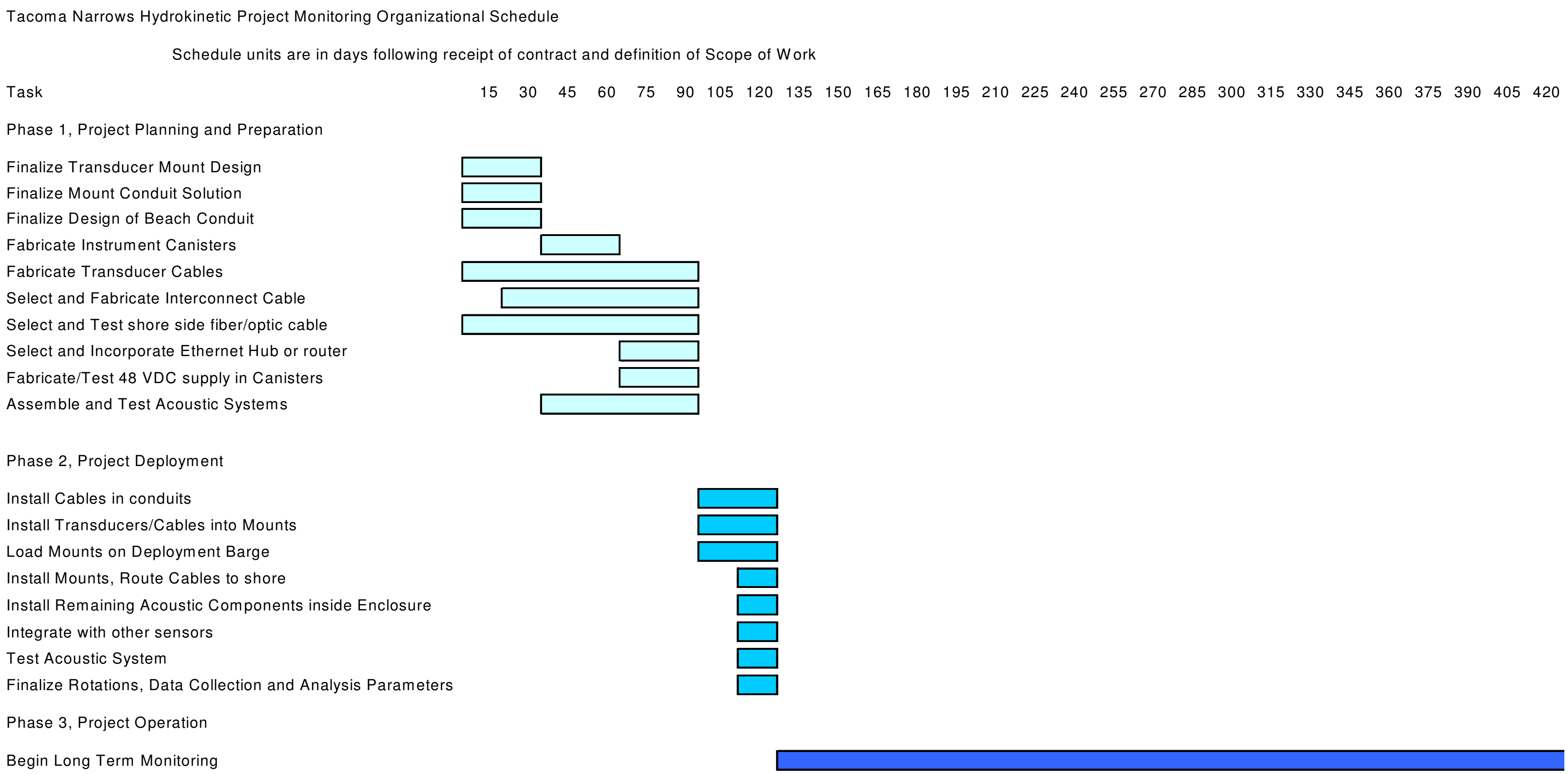


Figure 74. Proposed Project Schedule

Appendix A. The Verdant Experience

Introduction

BioSonics began working with Verdant Power in 2004 by monitoring for fish and diving birds in the Merrimack River as Verdant tested out a Gorlov Helical Turbine. Regulators at this project needed assurance that the turbine was not impacting the fish and diving birds. BioSonics created a mechanical reporting process that manually extracted fish counts from a computer screen. After developing pre-test and within-test monitoring protocols, as well as a stand-down protocol if negative impacts were observed, turbine testing was allowed to proceed. These protocols provided the seeds from which Verdant Power, Devine Tarbell and Associates, and BioSonics developed the Roosevelt Island Tidal Energy study plan.

Study Plan Development

Since no baseline monitoring was completed prior to installation of the two phase 1 turbines, the study plan called for an acoustic curtain (created by 3 split-beam transducers stacked vertically) to be installed immediately up-current and down-current of each turbine pair. Two additional acoustic curtains were included, one up-current of the study footprint and one down-current, to provide fish counts and distributional data up-current of the hydraulic influence and down-current of the turbine array. When 2 additional turbine pairs were installed in Phase 2, four new acoustic curtain systems were installed immediately up-current and down-current of the turbine pairs (Figure 13). Regulatory agencies approving this study plan included National Marine Fisheries Service (NMFS), U. S. Army Corps of Engineers (USACE), U. S. Fish and Wildlife Service (USFWS), and New York Department of Environmental Conservation (NYDEC).

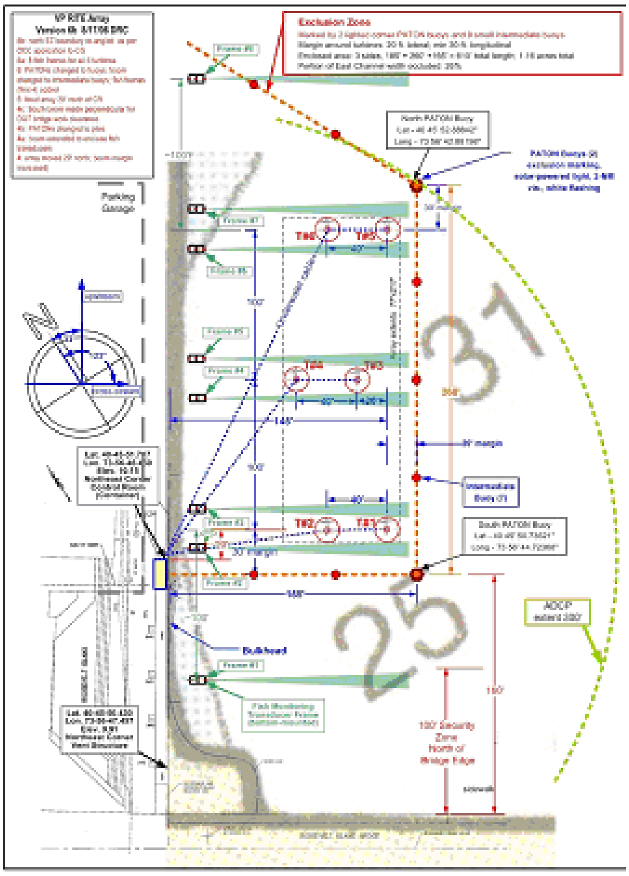


Figure 175. Plan View, RITE Turbines and Acoustic Curtains

System Installation

BioSonics scientific personnel assisted in the design, fabrication, and installation of the transducer mounts and the acoustic system. Assembled transducer mounts were lifted from a jack-up barge (Figure 14) and placed on the rip-rap slope of the west bank of the East River. Cables were routed through plastic conduit to the control room, where they were passed inside through a weatherproof opening and attached to the echo sounders and computers. Verdant installed a bottom-mounted ADCP and routed the cable back to the control room to provide streaming current data. After each frame (Figure 15) was installed, it was surveyed to determine the exact position and orientation on the river bottom. These data sets were used to transform acoustic coordinates of each detected fish target into real-world or river coordinates, allowing correlation of fish position with turbine blade position.

Figure 176. Jack-Up Barge for Installing Turbines and Transducers

Figure 15. RITE Transducer Mount Deployment

Monitoring and Reporting

The acoustic monitoring has been ongoing for over 1 year with no failures involving the acoustic equipment. The acoustic data from the 8 curtains or screens are analyzed by fish counting software and results are compiled by hour. At the end of each day, hourly estimates of fish counts and mean fish size are calculated in each of the analytical cells (Figure 16) and a daily summary report is calculated. The report documenting observed ALERT conditions

(Figure 17) and a detailed report of target detections by analytical cell are automatically emailed to authorized project personnel each day. Diagnostic software running in the background on the control room computers alerts project personnel to most equipment and computer hang-ups, and is programmed to automatically re-boot and re-start the monitoring system when abnormal conditions are detected.

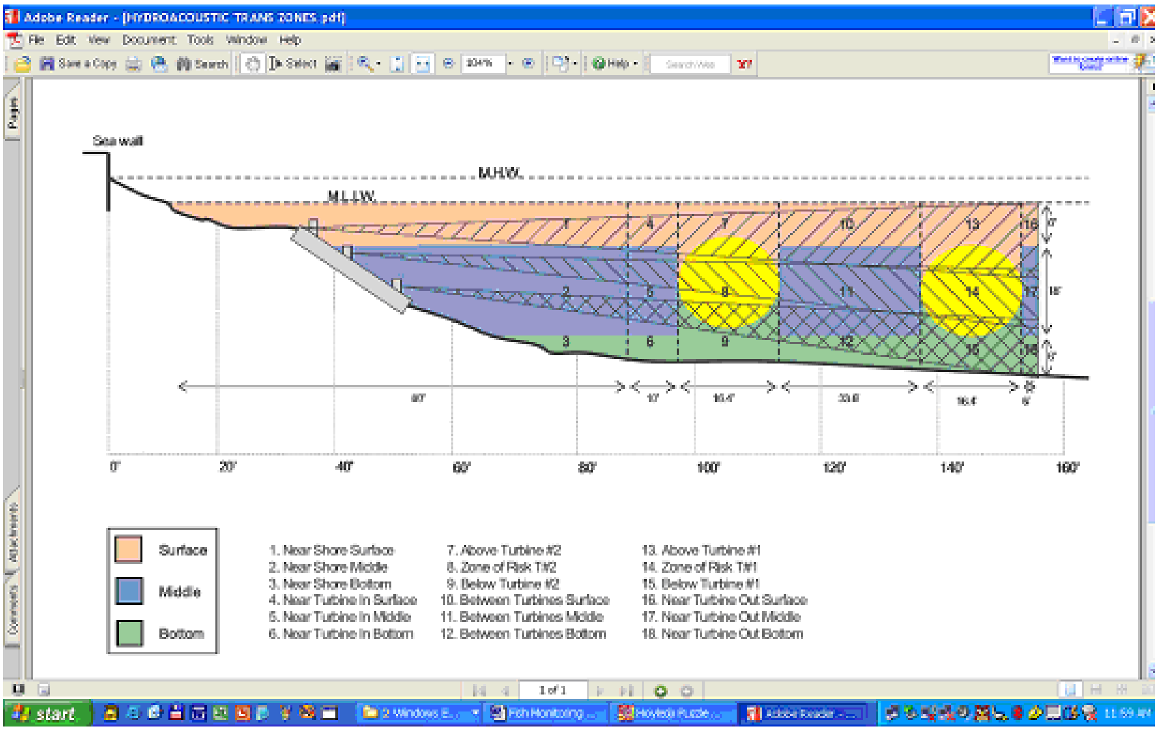


Figure 177. RITE Cross-Section with Analysis Grid

Nearfield events for Turbines T1 and T2 for 2007/01/20
Roosevelt Island Tidal Energy Project
BioSonics, Inc.

	Alarm 1	Alarm 2	Alarm 3	Alarm 4	Alarm 5	Alarm 6	Alarm 7	Alarm 8								
Day	0	0	0	0	0	0	0	0								
Time	Alert_1	Alert_2	Alert_3	Alert_4	Alert_5	Alert_6	Alert_7	Alert_8	Event_1	Event_2	Event_3	Event_4	Event_5	Event_6	Event_7	Event_8
0:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	51	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	1	0	86	0	0	1	0	0	1	0
7:00	0	0	0	0	0	0	0	0	53	0	0	1	0	0	0	0
8:00	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
15:00	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	56	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0	0	79	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	67	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	41	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	0	0	0	0	0	0	1	0	493	0	0	2	0	0	1	0

Figure 78. Example of RITE Automated ALERT Report

Appendix B. Shore Side Infrastructure

Borrowing from the decisions and terminologies of Verdant Power's RITE project, a central enclosure was installed as close to the proposed turbine locations as possible and called the "Control Room". This structure was a steel cargo container. Power was available from a shore side utility, and further, the connection to the utility was designed such that power generated by the turbines could be pumped back into the grid through the same connection. This control room has Air Conditioning and Heat, as well as a phone line and a connection to a high speed broadband Internet provider (Figure 18).

Figure 79. RITE Control Room

This control room can be considered the project center, and it is in this location that important visitors (from government, media, regulators, etc.) will congregate to observe the project progress. Thus, the location needs to look professional. (Installation of a Sani-Can near by would also be a good idea.)

If the control room overlooks the section of water in which the turbines are installed, installation of web cams would benefit team members. These camera views could be aimed out over the water above the turbines. If anomalous readings are observed on the acoustic monitoring system, project personnel can log into the project over the Internet and look out at the study footprint to see if any unusual surface activity is taking place. Web cams surveying the control room door and the inside space would provide additional security. Fuhrman Diversified manufactures a solid state video recording system for long term video recording. Finally, it would be appropriate to be sure that local police know where the control room is and how to get there quickly.

Appendix C. Transducer Mount Design, Fabrication, Installation and Cable Routing

BioSonics traditionally designs and fabricates transducer mounts for its acoustic monitoring projects. We have considerable experience around dams and in rivers, but little in marine tidal areas. Verdant power designed and fabricated the transducer mounts for their East River project, with some consultation from BioSonics scientists and engineers. Evans-Hamilton has designed and fabricated mounts for electronic instruments that are trawl and rope snag resistant. Project resources would be efficiently used by trying to modify one of their existing designs.

In terms of design requirements, the mount must provide a protected environment for the transducer and rotator and cables. It must have enough inner volume to enclose the electronics pressure canister (a cylinder approximately 16” diameter by 30” long), the dual-axis rotator, the split-beam transducer, and the transducer cable and connector. It must allow for a specific degree of rotation by the transducer. A cut-out must be provided to allow the acoustic beam to be transmitted into the water in an unobstructed manner, much like an observatory has a slot through which the telescope is pointed. The mount must have attachment points for a lifting harness. The harness and these lifting points must not compromise the view of the transducer or affect the snag resistance of the mount design. The mount must be either heavy enough to stay on the bottom and not be moved by the high tidal currents, or must be attached to the bottom with some type of anchoring system. The mount must provide an absolutely rigid and unmoving platform for the transducer, or movement of the mount will degrade the acoustic returns.

The mount may or may not be designed to require a diver during installation. It is worth mentioning again that the mount installation time windows are likely of short duration during slack tide periods. We suggest that the mount designer also be the team member that designs the deployment/installation strategies and directs these activities in the field.

At present, separate mounts are proposed for the two acoustic systems. If bathymetry permits, we can consider building a larger mount that houses two transducers, two rotators, and two pressure canisters. If two mounts are used, they will be connected by a power/signal/Ethernet cable. This connection presents some conceptual problems in that it implies that the two mounts are connected. This connection adds complications during the installation process in that the cable between the mounts may require that both mounts be installed on the same tidal cycle – this may be impossible or impractical due to the short duration of slack water. A surface vessel would likely have to leave the area and return at next slack water. One method to deal with the short duration of slack is to use a jack-up barge for the installation platform - it may be able to stay in place throughout a tidal cycle. If water depth is too great for a jack-up barge, a buoy and anchor could be temporarily positioned near the first mount, and the interconnect cable brought up the buoy line and tied off. At next slack, the end of the interconnect cable could be retrieved from the buoy, attached to the second mount, and the mount dropped into position. Following installation of the second mount, the fiber-optic/power cable would be routed to the shore. This cable would need to be protected from the current, and also from fishing gear and boat anchors. We believe that other team members have more expertise in this area and would be able to design a protective system for both installation and routing of this fiber-optic cable. The conduit should have a structural connection to the mount. BioSonics will assist the team member that takes on this task – funding for consultation is built into the Project Preparation section of our budget.

Appendix D. Additional Sensors

Other team members have experience in underwater sensors. We propose that the Project Leads decide to install an Acoustic Doppler Current Profiler in the study footprint. This sensor would be bottom mounted and would stream data back to shore and into the control room. This direct measure of direction and velocity of current would provide valuable data to turbine operators, and would allow the acoustic system to designate all detected targets as moving with or moving against the current. The mount for this sensor would have to be able to withstand the strong currents and not be moved. The placement of the ADCP mount should be in the “RED” zone of the current velocity map (Figure 5). The signal cable would have to be protected from the flow and from anchors and fishing gear.

Installation of a streaming CTD sensor, perhaps inside one of the transducer mounts, would provide a real-time flow of salinity and temperature data. This data set will be used to program the environmental parameters of the echo sounder automatically, and would be useful when interpreting fish migrations and other acoustic patterns. These signals would require routing another signal cable to shore, or perhaps could be routed through the existing signal cables used by the acoustic system.

Installation of a weather station at or near the study footprint would provide valuable data to the project. The project should seek to have real-time access to this data set in the control room. If off-site project scientists logged into the acoustic system to evaluate strange readings, it would be valuable to have access both to the weather station data and the web cams to explain local conditions.

Appendix E. Marking of Study Site (Site Demarcation)

The project study footprint will likely be defined as a region stretching out from shore to some defined distance such as 300 m, and as a region stretching north and south of the actual monitoring site. In early project phases, it is likely that the only gear in the water will be acoustic monitoring and environmental monitoring sensors. In later phases, when one or more turbines are installed into the region, the study footprint may extend up and down current to a distance where turbine hydraulic effects are deemed insignificant. The location of this changing footprint will have to be negotiated with Coast Guard and perhaps the US Army Corps of Engineers, since the site is a navigable waterway. The study footprint will eventually have to be marked with surface buoys or other visible markers. It is critical to mention that surface markers and their anchoring lines often introduce bubble streams into the water and confound the acoustic monitoring equipment. We strongly recommend that BioSonics participate in discussions on how to mark the site. After it is determined how and where to put site markers, the markers will have to be published in Aids to Navigation.

Appendix F. Miscellaneous BioSonics Thoughts

Earlier sections have introduced the implementation of other sensors. BioSonics engineers will be able to interface the outputs of these sensors with the data flow from the acoustic systems, providing the data are supplied digitally inside the control room.

In an earlier section, we mentioned the FERC strategies to mitigate project risk. The last step was to remove or shut down a project. This strategy may provide an unacceptable risk to many investors. A more suitable strategy is to be able to shut a turbine off when an unacceptable risk is detected or predicted. The acoustic system can provide the detection capability and the communication message to the turbine. We suggest that turbine manufacturers strongly consider designing in either a braking system or an ability to vary the propeller pitch to neutral, thus stopping blade rotation. If this capability exists in the turbine, then regulators will likely have a higher comfort level with a hydrokinetic project that can be stopped by biologically triggered events. Additionally, turbine vendors need to build in a communication protocol so that commands can be sent to and received from the turbine.

The high flows typical of a hydrokinetic project imply significant risk to both turbines and blades. We suggest that turbine vendors consider designing their systems so that blades can be replaced relatively easily, perhaps by scuba divers. We observed at the RITE project in New York City that when turbine blades were broken by impact with objects or by high flows, the project then incurred the high cost of removing the entire turbine from the floor of the river. Turbine designers should evaluate the possibility of a design in which the propeller hub could be quickly removed by a scuba diver and hoisted to the surface. It could be argued that blade damage is inevitable: the strategy of easy propeller removal would substantially reduce maintenance costs.

Many turbine designs utilize a rigid mount attached to the bottom substrate, such as a monopile. Using the same logic as we did for damaged propellers, the project would benefit by designing turbines that could easily be removed from their mount and from their electronic cable. In such a scenario, a diver would approach the defective unit at slack tide, attach a floatation collar to it, disconnect the turbine from its mount and cable, and inflate the floatation collar to lift the unit to the surface where it could be towed or lifted to a work area.

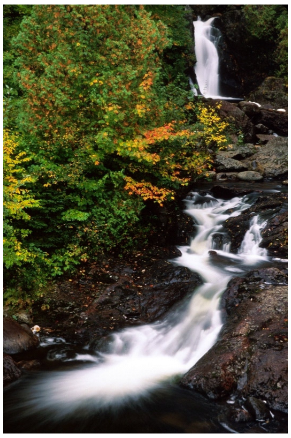
When turbines are installed and are left over long periods of time, it is almost inevitable that a drifting rope will foul them. Several manufacturers produce a cutting tool for boat propellers that will cut fouled lines off automatically. We suggest that such technologies be evaluated to determine if they could be scaled up to provide protection for hydrokinetic turbines.

Appendix 4: Cost of Energy Analysis

Cost of Energy Analysis for Tacoma Power Tidal Project Phase II Feasibility Study

Final Draft
17 December 2007

Prepared by:



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This investigation, analysis, and subsequent report are subject to important conditions and assumptions that affect the findings and conclusions. Applicable data gaps, or lack of supporting documentation, are identified throughout the report. The reader should review all limiting conditions and assumptions contained in this report before utilizing or relying upon the conclusions and findings.

Resource Dimensions team *(in alphabetical order)*:
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Acknowledgements

This report has been prepared with the assistance of many people, to all of whom great thanks are extended. Specific thanks are due to the City of Tacoma, Tacoma Power project manager Scott Amsden, as well as Chris Robinson, Debbie Young and other Tacoma Power staff assigned to this project. The challenges of leading any field are many and we value the unique contributions and expertise of the colleagues drawn together by this project to explore the potential for tidal power generation.

Renewable energy will increasingly be required to supply a greater share of our energy requirements worldwide. Renewable resources are truly vast. As with the potential for tidal power, it is our current knowledge and available technology, which limits us. Exploration as that undertaken by the Tacoma Narrows Tidal Energy Feasibility project will continue to expand our knowledge and improve methods by which we might harness the earth's forces in ways that will lead to a healthier and more sustainable future for all. We would like to thank the Bonneville Power Administration and the City of Tacoma for their financial support of this project and other renewable energy research.

[21] Corresponding author and co-principal investigator
[22] Principal and co-principal investigator/project lead economist

Executive Summary

The Big Picture

Tacoma Power is a municipal utility that will be required to meet the I-937 mandate. While their generating asset portfolio is substantially composed of clean hydroelectric power plants, they lack facilities eligible to produce RECs.[23] Tacoma Power has three options: (1) look to the REC market to acquire the necessary RECs; (2) pay the penalty price, or; (3) expand their portfolio to include REC eligible power plants. This feasibility study is part of the effort by Tacoma Power to determine a course of action and provide the best response in serving the interests of Tacoma, Washington ratepayers.

The Analysis

This economic feasibility analysis is based on calculating and comparing levelized cost of electricity (COE) from a proposed tidal power plant to be deployed in the Tacoma Narrows. The standard used by the electric supply industry to evaluate the economic feasibility of a power plant is the levelized cost of electricity method. This is a monetary unit in cents per kilowatt-hour (¢/kWh) that allows comparison between different power projects with regard to plant generating capacity, project life, capital construction costs, annual costs, fuel costs, cost of capital, annual expenses, discount rates, etc. It is a common matrix by which to compare diverse and otherwise difficult to compare projects.

The analysis consists of calculating the COE for a baseline scenario and conducting sensitivity analysis based on changes to different project characteristics or assumptions: (1) a change in the Total Plant Investment (TPI) cost; (2) a change in the Annual Overhaul and Maintenance (AO&M), and (3) a change in the technical efficiency of the turbines, and (4) the best alternative renewable energy project, a newly constructed commercial-scale wind farm.[24]

[23] I-937's definition of renewable energy does not include many existing hydroelectric facilities.
[24] NOTE: all cost estimates developed for this project have been projected from preliminary data. Continuing efforts to improve and advance the technology and to secure pilot projects will serve to improve our knowledge relative to costs that will enhance future COE projections significantly.

Summary of Cost of Energy (COE) Feasibility Analysis Findings

The baseline tidal power plant project as proposed is a best-case scenario. It has the following characteristics:

Baseline Scenario	
Rated Plant Capacity	22.43MWh(a)
Annual Electric Energy Production	196,000 MW/year
Constant Dollars	2007
Commission Year (start of year)	2011
Book Life	30 years
Construction Financing	6.0% per annum
Debt Financing Bond	100%
Debt Financing Rate	6.0% per annum
Inflation Rate	3.0% per annum
Discount Rate	6.0% per annum
Cost of Insurance	1.5% per annum of Total Plant Cost
Efficiency of Turbine Array	50%
Number of Turbines	88 (double rotor)
Total Plant Cost	$138,770,000
Total Plant Investment	$145,560,000
Annual O&M	$7,830,000 per annum

Table 1 below shows that the cost of electricity for the proposed best-case tidal power plant is 8 cents per kilowatt-hour (8.0 ¢/kWh).

Table 1 Cost of Electricity (¢/kWh) – Baseline Scenario

Total Project Investment ($million)	**145.6m**
Levelized Annual O&M	
7.8m	**8.0** **(5.7)**
Nominal $2007*(Constant value)*	

The Total Project Investment (TPI) is the amount of permanent long-term capital financing for the tidal power plant. TPI is the initial upfront cost paid out to create the project. It amounts to $145.6 million. The Levelized Annual O&M (AO&M) cost includes all the expenses associated with operating and maintaining the project over its life, than levelized to an annual average. This recurring cost is $7.8 million. These two costs, TPI and AO&M, determine the cost of electricity (COE) that represents the minimum charge for electric power that must be collected for the tidal power plant to breakeven

The COE for the baseline scenario is 8.0 ¢/kWh in nominal terms[25]. The COE of 5.7¢/kWh, within parentheses, is constant or real terms[26].

Table 2 depicts the cost of electricity sensitivity analysis for changes in TPI costs projected for the tidal power plant designed for deployment in the Tacoma Narrows.

Table 2 Cost of Electricity (¢/kWh) – Sensitivity to Changes in Total Plant Investment

Total Project Investment ($million)	**116.5m** (20% decrease)	**145.6m Baseline**	**174.7m** (20% increase)	218.4m (50% increase)
Levelized Annual O&M				
7.8m (fixed)	7.2 (5.5)	8.0 (5.9)	8.8 (6.2)	10.0 (6.8)
% change in COE from Baseline	-10.0%	0.0%	10.0%	25.0%
Nominal $2007 *(Constant value)*				

For comparative purposes, Table 3 below shows the COE of a tidal power plant that would be competitive with a new build wind farm. The baseline scenario assumes, the tidal power plant is built and has a TPI cost of $145.6 million and an AO&M of $7.8 million. The analysis estimates the level of construction cost subsidies that would be required to decrease the TPI to be recovered to a level that the leads to a 5.0 ¢/kWh COE.

Table 3 Cost of Electricity (¢/kWh) – Equivalent COE to New Wind Systems

Total Project Investment ($million)	**36.25m**
Levelized Annual O&M	
7.8m	**5.00 (4.46)**
Nominal $2007 (Constant value)	

For the tidal flow power plant to be competitive with a newly constructed wind farm on a COE basis, the TPI cannot exceed $36.25 million. This means that a subsidy of

[25] A nominal COE value represents the actual cost without adjusting for inflation during the period of time the costs are incurred, in the case of the baseline scenario this period is 30 years. .

[26] A constant COE value represents the actual cost with adjustments for inflation during the period of time the costs are incurred.

$109.3 million would be required for the tidal power plant to produce electricity at 5.0 ¢/kWh. This represents a 75% reduction in Total Plant Investment.

Clearly, the tidal power plant under consideration is not economically feasible at this time. With a COE of 8.0¢/kWh for the best-case scenario baseline project and a COE of 7.0¢/kWh if TPI costs are reduced by 20% from the best case. The project, as proposed, cannot compete with many of the alternative renewable energy projects that currently can be deployed at commercial scale. However, over the medium-term, it is expected that as technological experience is gained, the “best-case” scenario will improve and the proposed project would become competitive.

List of Acronyms

¢/kWh	Cents per kilowatt-hour
AEP	Annual Electricity Produced
AFUDC	Allowance for funds used during construction
AO & M	Annual Operation and Maintenance cost
BMP	best management practices
BT	Benefits-transfer; an economics approach used to assess values in a particular case or setting based on information learned from other studies removed by time and/or place.
COE	Cost of energy
CRF	Capital recovery factor
CREB	Clean Renewable Energy Bonds
CFS	Cubic foot of water per second of time; one CFS is equal to the discharge of a stream of rectangular cross section, 1 foot wide and 1 foot deep, flowing water an average velocity of 1 foot per second.
DNR	Washington State Department of Natural Resources Ecology Washington State Department of Ecology
FCR	Fixed Charge Rate
FY	Fiscal year
LO&R	Levelized Overhaul and Replacement Cost
LRC	Levelized Replacement Cost
MWh	Megawatt hour
NPV	Net present value
REC	Renewable Energy Certificates
REPI	Renewable Energy Production Incentive
RPS	Renewable Portfolio Standards
TPI	Total Plant Investment

Introduction

Overview

Different power generation technologies have specific characteristics that may vary considerably from one technology to another. Such characteristics as permitting and construction time, electrical output, project operating life, capital investment, fuel source (price and price volatility), operating costs and maintenance all influence the cost structure of the projects. These differences make it very difficult to compare not only between technologies but also between different characteristic levels with-in the same technologies.

The standard methodology used to perform a comparison between alternative electric power generation projects is the levelized cost methodology. This method is generally accepted for use by regulated public utilities and by regulatory commissions throughout the United States.

The levelized cost of electricity is the mean value of the present worth[27] annual revenue needed to cover the present worth total costs associated with the power plant during its service life divided by the mean annual electricity produced by the project. This calculation provides a monetary value in cents per kilowatt-hour (¢/kWh) in nominal terms that can be used to compare between types of technology and variations within the same technology types.

Tacoma Power is classified as a municipal electric utility[28], commonly called a municipal generator, and is treated in a different manner than a investor owned utility which operates to earn a profit and return on investment for its owners. Certain costs that apply to for-profit power generators are not included in an analysis of Tacoma Power: Return on Equity, State Taxes, Federal Taxes, State Tax Incentives, Federal Tax Incentives, Accelerated Depreciation, and Property Taxes.

In the context of this analysis, the annual revenue requirement of a municipal generator is defined as the annual cost to operate the tidal power project. The balance of costs and revenues just allow the operation to breakeven. The munici-

[27] Present worth is alternative term for present value.
[28] Municipal electric utility means a city or town that owns or operates an electric utility authorized by RCW Chapter 35.92.

pal generator adjusts its rates to cover operating expenses and recover the cost of capital assets.

Annual incurred costs are levelized by summing the net present value (NPV) for each year. The NPV is calculated using a discount rate that is determined by Tacoma Power as the cost of money over time. No adjustments need occur for tax rates.

The fixed charge rate is the percentage of the total plant cost that is required over the project life per year to cover the minimal annual revenue requirements. This fixed rate concept can be compared to a fixed rate home mortgage where a fixed annual payment will pay off the principal and interest over a specified time period.

It is calculated in three steps:

a) Calculate Capital Recovery Factor (CRF):

$$CRF = \frac{\text{Discount Rate}}{(1+\text{Discount Rate})^{\text{Book Life}} - 1} + \text{Discount Rate}$$

b) Calculate the levelized annual charges by multiplying the CRF by the NPV.

c) Calculate the levelized Annual Fixed Charge Rate by dividing the levelized annual charges by the Total Plant Investment (Booked Costs)

Calculating the Cost of Energy

The levelized cost of electricity is derived by dividing the annual cost of the power plant by the annual energy production.

$$\text{Levelized Cost of Electricity} = \frac{(TPI * FCR) + (O\&M) + (LO\&R)}{AEP}$$

where:

TPI	= Total Plant Investment
FCR	= Fixed Charge Rate (percentage)
O&M	= Annual Operating and Maintenance Cost
LO&R	= Periodic Levelized Overhaul and Replacement Cost
AEP	= Annual Electricity Produced at Busbar

Annual electricity production (AEP) is estimated from the average tidal measurements and the power generation values for the turbine under consideration. The AEP is assumed constant over the life of the project.

Cost Components

Various costs associated with a tidapower plant are presented here. All capital expenditures are defined as installed costs and expressed in constant dollars; 2007 is the base year.

Structural Construction Components (Hardware)

- **Turbine:** All components that are directly responsible for the extraction of energy from the tidal flow, such as rotors, control mechanisms, and power transfer shaft.

- **Extractor Structure:** All required structural components including housing ducts and other structural components.

- **Power Take Off:** Converts the slow movement of the turbine via gearing or hydraulics and generator into electricity.

- **Foundation/Mooring/Anchorage:** All components required for holding the turbine in place.

- **Electrical Interconnection:** All cables required to interconnect the individual turbines to a common interconnection point in or close to the tidal channel.

- **Communications, Command and Control:** All equipment and infrastructure required to establish a two-way link from land-based to tidal channel-based systems for purposes of communication, command and control.

Non-structural Construction Components

- **Installation Cost:** The costs required to transport the system from its safe harbor assembly location to its deployment site and complete all interconnections and checkout the point where the system is ready to begin official commissioning procedures.

- **General Facilities and Engineering:** Engineering cost associated with the planning of a tidal power plant and general facilities required for deploying and operating the power plant. This could include necessary dock modifications, maintenance shops, etc. for the deployment and maintenance of the tidal power plant as well as the mobilization of the O&M itself.

- **Commissioning:** The process, inspection and testing required to turn over the system from the general contractor to the owner/operator.

- **Spares Provision:** 2% of the hardware costs above.

Grid Network Interconnection Costs

- **Grid Interconnection:** All cabling, switchgear, transmission lines and infrastructure required to connect from the common interconnection point of the tidal power plant to a nearby land-based grid interconnection point.

- **Substations to Substation Upgrade Cost:** This cost is not factored into the cost of electricity as the initial costs may be credited back to the tidal power plant owner/operator under customary practices of the industry. This cost would not be incurred for the proposed project, as the entire system is owned by Tacoma Power.

Owner's Costs

- **Owner's Development Costs:** Assumed to be 5% of the costs through installation above.

- **Financial Fees:** 2% of the 1st year debt with the cost occurring in the 2nd year of the two-year construction period.

- **Interest During Construction:** Interest paid for the two-year construction loan (assumes two loans, one at the beginning of each year).

AO&M Costs

- **Annual Scheduled O&M cost:** The components of AO&M costs are insurance, labor and parts. Labor is broadly defined to include equipment such as barges, dive boats, etc, necessary for personnel to carry out the O&M operations. Parts are simply replacement items. The O&M costs do not include the infrequently incurred costs of major overhauls of turbines devices or other components. These costs are included in the levelized overhaul and replacement cost (LO&RC). Expenses are annual payments associated with plant operations and maintenance (O&M), and include recurring O&M and non-recurring O&M.[29] The majority of the O&M costs associated with turbines can be grouped into three categories:

- Scheduled preventive maintenance for the turbines turbine and power take off system.
- Scheduled major overhauls and subsystem replacements of system devices.

- **Annual Unscheduled O&M Cost:** A provision for unscheduled maintenance is estimated at a fraction of the annual scheduled O&M Cost.
  - Unscheduled maintenance to carry out repairs, typically occurring after a violent storm.
- **Periodic Levelized Overhaul and Replacement Cost (LO&RC):** Depending on the specific manufacturers design, major overhaul of the device and mooring system is scheduled to occur every 5, 10 or 15 years. These major overhauls may address gears, bearings, seals and other moving parts as well as the mooring cable and components. Because these costs are incurred at intervals of several years and not routinely during each year, correct accounting for their costs requires an annual accrual of funds. The objective of this accrual is to have the funds available when the need for overhaul or replacement occurs. The accrual involves a net present value calculation to level or apportion the overhaul and replacement costs to an annualized basis consistent with the cost elements. Because they are treated as investment, for an investor owned utility they are eligible for investment tax credit, but are not so treated for Tacoma Power.

Aggregated Cost Definitions

The following defined costs are composed of the above listed costs.

- **Total Plant Cost (TPC):** This is the total installed and commissioned cost of the power plant and consists of the above-mentioned cost elements.
- **Total Plant Investment (TPI):** Total Plant Investment is the amount of the capital required to build the power plant. TPI = TPC + Interest during Construction.[30]

[29] The economic analysis estimates the O&M for the project based on related infrastructure projects from the offshore industry.

Incentives – Revenues from Production of Renewable Electricity

Three potential incentives or revenue streams exist from the production of qualifying renewable electricity.

Although incentives are available for this project, no incentives have been included in the COE sensitivity analysis described in the following sections.

Renewable Energy Production Incentive (REPI)

Municipal generators are eligible for a production incentive of 1.5 cents per kWh (based on 1993 dollars indexed to inflation) for the first ten years of operation for qualifying facilities installed between October 1, 2005 and October 1, 2061. The payment of the production incentive is limited by the funds authorized and made available by the Federal Government.

Tidal energy systems are not currently included within the list of qualifying facilities.

Clean Renewable Energy Bonds (CREB)

A CREB is a special type of bond, known as a "tax credit bond" that offers qualified issuers (government bodies and consumer-owned utilities) such as Tacoma Power the equivalent of an interest-free loan for financing qualified energy projects for a limited time. These bonds are non-interest bearing obligations that generate a tax credit for the taxpayer who has invested in the bond. The tax credit is claimed by the bond holder in lieu of interest payments from the bond issuer.

Renewable Energy Credits/Certificates (REC)

A REC is a certificate that represents the environmental benefits from generating a unit of electricity from qualifying renewable energy sources. These credits/certificates can be commercially traded and act as proof of purchase of renewable energy by the owner. RECs commonly operate in conjunction with Renewable Portfolio Standards (RPS). An RPS is a mandate that a certain amount of

[30] In the regulated world, this is called "allowance for funds used during construction" (AFUDC).

non-renewable electricity sold by a retail electricity supplier be complemented by renewable electricity. The mandate can be either a fixed quantity or a percentage of quantity sold during a specified timeframe.

The Tidal Project COE Model

The two major factors, and their assumption sets, devise the core inputs into the cost of energy model (COE). Elements of each is outlined below in Sections 5.1 (financial) and 5.2 (project).

Financial Assumptions

The following assumptions act as the foundation for calculating the levelized cost of electricity.

Reference year, is the year for the dollar value in which annual costs are expressed. To make monetary values comparable over long periods of time two items are required. The base year to which all values will be converted for comparison and the general economic inflation rate. The base year used in this analysis is 2007 and the inflation rate is assumed to be 3.0% per annum. In this analysis, the COE is reported in nominal terms, year 2007 dollars.

Book life or project life, is the period over which the annual costs are incurred. The book life for a project can have a major impact on the COE. Two effects are confounded within a change of book life. The first and most significant effect is that as the project life is shortened large costs incurred at the start of the project like the Total Project Cost (TPC) must be recouped at a faster rate. The annual amount to be recouped on a project would be 20% larger on a 20-year project than on a 30-year project. A second effect is that the net present value of costs that would have occurred further in the future now have a greater impact. As an example, a $10 million end of a project cost after 20 years would have a NPV of $3.3 million versus an NPV of $ 1.8 million for a project that lasted 30 years. This analysis and report assumes a book life of 30 years.

Construction financial rate is the interest rate at which banks or other financial institutions will lend for money during the construction phase of a project. In this analysis, the rate is assumed to be 6.0% per annum. The construction phase is assumed two years with two equal sums lent out at the beginning of each year.

Fifty-percent of the project cost at the start of year one and 50% of the project costs at the beginning of year two.

Permanent or long-term financing is assumed to be 30-year bonds with a nominal fixed interest rate of 6.0%. This bond debt is used to repay the construction financing and interest accrued during the two-year construction phase. The permanent financing will consist of 100% bond debt. No equity financing is possible as Tacoma Power is a municipal generator.

Nominal discount rate, Tacoma Power uses a rate of 6% per annum. The discount rate is based on the capital structure of Tacoma Power, its time value of money and the perceived risk of power plant projects investment. The 6.0% per annum rate is typical of the industry for municipal generators. **Tax adjustments,** Tacoma Power is a not-for-profit municipal entity. Under Washington State and Federal law, it holds no tax liabilities that must be considered in this analysis. Therefore, no adjustments for taxation are made.

Project Assumptions

The tidal flow power project will operate at 50% efficiency. That is, 50% of the kinetic energy of water flowing by the turbine blades will be converted into electricity delivered to the busbar. This value is derived from the tidal array output model.

Array configuration. The proposed project consists of 88 dual rotor turbines each comprised of one pylon and two rotators, and all necessary cabling and facilities to deliver power to the transmission network.

Power production. 196,500 MWh of electricity will be delivered from the array of 88 turbines (dual rotor). This value is derived from the tidal array output model.

Annual aMW. The tidal flow power plant will deliver 22.43 aMW during the course of a year.

Total installed turbine costs. Each installed turbine will cost $1.5 million. This includes the power conversion system, structural elements, and costs from actual installation. Note that 45% of the costs are installation related and 55% are costs of the machine and structure.

Cabling and connection of turbines to transmission network. Cost of cabling and connection of the turbines to an onshore transmission network interconnection is $4.1 million dollars.

Interconnection to grid. The onshore transmission grid interconnection is $1.7 million.

Annual O&M. AO&M includes labor, parts, insurance, environmental monitoring, and a purpose built marine servicing vessel will cost $7.8 million per annum.

Scenarios

This section assesses the COE from the proposed tidal power plant project. A baseline COE is calculated from the above assumptions, both financial and technical project description. Four alternative project cost structures are then examined for sensitivity of impact on COE.

The first alternative cost structure tests sensitivity to a change in the Total Project Investment (TPI). The second alternative cost structure tests sensitivity to a change in the Annual Overhaul and Maintenance (AO&M)costs. The third alternative cost structure tests sensitivity to a change in the efficiency of the turbines. The fourth alternative cost structure estimates the TPI level at which this project would be comparable to a new build wind farm.

Baseline Scenario

Description

Baseline Scenario	
Rated Plant Capacity	22.43MWh(a)
Annual Electric Energy Production	196,000 MW/year
Constant Dollars	2007
Commission Year (start of year)	2011
Book Life	30 years
Construction Financing	6.0% per annum

Debt Financing Bond	100%
Debt Financing Rate	6.0% per annum
Inflation Rate	3.0% per annum
Discount Rate	6.0% per annum
Cost of Insurance	1.5% per annum of Total Plant Cost
Efficiency of Turbine Array	50%
Number of Turbines	88 (1 pylon with dual rotors)
Total Plant Cost	$138,800,000
Total Plant Investment	$145,600,000
Annual O&M	$7,830,000 per annum

Table 6.1 depicts the cost of electricity for the baseline scenario. The baseline is a best-case scenario, with the project being built as designed and meeting all assumptions that have been stated. The cost of electricity is 8.02 cents per kWh in nominal dollars. This value is based on a tidal power plant that costs $145.6 million at the time of commissioning in 2011 and has annual expenses of $7.8 million during its 30-year life. This project ranks among the most expensive of available generation technologies.

Table 6.1 Cost of Electricity (¢/kWh) –Baseline Scenario

Total Project Investment ($million)	**145.6m**
Levelized Annual O&M	
7.8m	**8.02** **(5.86)**
Nominal $2007 *(Constant value)*	

The 8.02 ¢/kWh can be compared to other technologies, both eligible and ineligible to meet the Washington State mandate for renewable energy credits.

The California Energy Commission (2005) has published estimated cost of energy values for a number of different power generation technologies. These costs are not directly comparable as the values are expressed in 2003 dollars, but the general range and magnitude of COE can be used to determine the relative position of tidal power to other technologies.

Cost of Electricity Generation ($2003 Current):

Technology	COE (¢/kWh)
Hydro	0.25 to 2.7
Coal	1.8 to 2.0
Natural Gas	5.2 to 15.9
Nuclear	8.3 to 11.1

For alternative low-carbon technologies:

Technology	COE (¢/kWh)
Solar	13.5 to 42.7
Wind	4.6

For new build generating facilities:

Technology	COE (¢/kWh)
Hydro (<30MW)	6.0
Coal	3.3 to 4.1
Natural Gas	5.2 to 15.9
Solar	13.5 to 42.7
Wind	4.6

Two cost factors are the principle drivers of the COE calculation; the TPI, the initial capital outlay plus interest payments to construct the power plant, and AO&M, the annual expenses incurred in operating and maintaining the power plant. This first cost constitutes a stock investment at the start of a project while the other constitutes a flow of costs over the project lifetime. Sensitivity analyses to these two major determinants are presented in the following section.

Sensitivity to Change in Total Plant Investment

The TPI is a large and significant cost at the start of the project life. It has a decreasing impact within the COE calculation, the longer the period over which it is discounted.

The change in TPI is assumed to result from changes in the Total Project Cost (TPC), not from a change in the construction timeframe or construction lending rate. TPI is used as opposed to the TPC, as the TPI value is assumed to be the amount funded by permanent financing.

Four alternative capital investment scenarios are presented below. The TPI is changed in three scenarios. The second scenario is the TPI as determined in the baseline case.

The three comparative scenarios use a modified Annual Overhaul and Maintenance value. All AO&M costs are held constant at the baseline scenario value with the exception of project insurance costs. The annual insurance premium (1.5% of TPC) is varies for the three comparative scenarios. The allowance within the AO&M cost gives a more accurate comparative COE for each scenario. The modified AO&M cost is $5.8 million plus change in insurance premium.

Scenario 1

The first scenario assumes that uncertain knowledge of building a tidal power plant project leads to inflated costs to allow for the related risks. To account for this the TPI is decreased by 20%.

Scenario 2

The second scenario is the baseline project profile given above.

Scenario 3

The third scenario assumes that uncertain knowledge of building a tidal power plant leads to deflated costs do to uncertain knowledge of the process in building and commissioning the project. In addition, advocates of the technology may underestimate costs due to technological optimism. To account for this the TPI is increased by 20%.

Scenario 4

The forth scenario assumes that uncertain knowledge of building a tidal power plant was fundamentally flawed. The increased costs came from unanticipated costs overruns as well as costs that were not recognized before hand. To account for this the TPI is increased by 50%. This level of cost increase was deemed sufficient for this analysis. In practical terms the potential costs overrun, given the global lack of commercial-scale expertise in tidal energy projects, could be far greater.

Summary of Sensitivity Analysis to Total plant Investment

Table 6.2 below presents the COE resulting from a change in TPI from the baseline case. It can be seen that the effect on COE is a non-linear relationship to the change in TPI. A relative increase or decrease in TPI has a lower proportional increase or decrease in COE.

Table 6.2 Cost of Electricity (¢/kWh) – Change in Total Project Investment

Total Project Investment ($million)	**116m** (20% decrease)	**145m Base-line**	**175m** (20% increase)	218m (50% increase)
Annual O&M (Modified Value)				
5.8m + insurance cost*	7.00 (5.28)	8.02 (5.86)	9.04 (6.45)	10.56 (7.32)
% change in COE from Baseline	-12.7%	0.0%	12.7%	31.7%
Nominal $2007 *(Constant value)*				

* Insurance costs are 1.5% of TPC.

Under Scenario 1, a 20% decrease in constructing a tidal power plant leads to less than a 13% decrease in COE. This is 7.0 ¢/kWh in current dollars. In conditions for Scenario 4, a 50% increase in initial capital investment would lead to a 10.56 ¢/kWh COE or a 31.7% increase. This is because the discount rate gives substantially less weight or value to expenses incurred in the distant future.

Sensitivity to Change in Annual Overhaul and Maintenance Costs

The AO&M is another major determinant of the COE. The AO&M cost continues to have a relatively large impact as the annual cost is not discounted, it is assumed to maintain its value from year to year throughout the project life. This is unlike the TPI, which has a decreasing impact on COE as time progresses due to the effect of discounting.

Four alternative AO&M cost scenarios are presented below. The AO&M cost is changed in three scenarios, while the forth scenario is AO&M cost as determined in the baseline case.

In this analysis, there is no necessity to modify the normal calculation of the AO&M cost or the TPI as in Section 6.2, which addressed sensitivity to TPI. All changes in AO&M costs are the result of changes in the labor and parts category.

Scenario 1

The first scenario assumes that uncertain knowledge of operating, overhauling and maintaining a tidal power plant lead to inflated costs to allow for the related risks. To account for this the AO&M cost is decreased by 20%.

Scenario 2

The second scenario is the baseline project profile given above.

Scenario 3

The third scenario assumes that uncertain knowledge of operating, overhauling and maintaining a tidal power plant lead to deflated costs in relation to true costs and related risks. In addition, the advocates of the technology may underestimate costs due to technological optimism. To account for this the AO&M costs is increased by 20%.

Scenario 4

The third scenario assumes that uncertain knowledge of operating, overhauling and maintaining a tidal power plant lead to deflated costs in relation to true costs and related risks. In addition, the advocates of the technology may underestimate costs due to technological optimism. To account for this the AO&M costs are increased by 50%. This level of cost increase was deemed sufficient for this analysis. In practical terms, the potential cost overrun, given the global lack of commercial-scale expertise in tidal energy projects, could be far greater.

Summary of Sensitivity Analysis to Total Plant Investment

Table 6.3 below presents the COE resulting from a change in AO&M costs from the baseline case. The effect on COE is a linear relationship to the change in AO&M costs. The proportional increase or decrease in COE is seen to have an impact equal to 50% of the relative increase or decrease in AO&M costs. Each 1% change in AO&M costs results in a 0.5% change in the COE, in the same direction.

Table 6.3 Cost of Electricity (¢/kWh) – Change in Levelized Annual O&M

Total Project Investment ($million)	145m Baseline	% change in COE from Baseline
Annual O&M		
6.7m (20% decrease)	7.22 (5.06)	-10.0%

7.8m Baseline	**8.02 (5.86)**	0.0%
9.4m (20% increase)	8.82 (6.66)	10.0%
11.8m (50% increase)	10.02 (7.86)	24.9%
Nominal $2007 *(Constant value)*		

Under Scenario 1, the marginal change in COE from a 20% decrease in operating and maintaining a tidal power plant results in a 10% reduction in annual costs. In current dollars, this represents a decrease to 7.22 ¢/kWh from 8.02 ¢/kWh. A 50% increase in operating and maintaining the project, as under Scenario 4, leads to a COE at 10.02 ¢/kWh or a 25% increase in cost.

Sensitivity Analysis to Competitive COE Levels

The baseline project is the best case scenario for a tidal power plant. One of the key assumptions in the baseline profile is that the turbine design will be highly efficient at converting energy from moving water into electricity. The assumed efficiency of 50% is not technically possible at this time, but may be possible in several years as more design and engineering experience is gained.

The importance of turbine efficiency is critical to the COE. The costs of the project, TPI and AO&M, are averaged out over the expected annual electricity production from the tidal power plant. Any reduction in efficiency directly translates into higher COE values.

Table 6.4 below shows the change in cost of electricity that would occur if lower efficiencies were to be realized once commercial-scale deployment occurred.

Table 6.4: Cost of Electricity (¢/kWh) - Change in Turbine Efficiency

Turbine Efficiency	Baseline Project (145m TPI and 7.8m AO&M)	% change in COE from Baseline
20%	19.92 (5.06)	150%
30%	13.28 (9.70)	67%

40%	9.96 (7.28)	25%
50% Baseline Case*	7.97 (5.82)	0%

Nominal $2007 *(Constant value)*

*Note: *The actual baseline project was proposed with a 49.8% efficiency assumption. The COE at 50% is marginally less than the values given for the baseline project.*

A turbine operating at 20% efficiency, not the assumed 50% level, will have a cost of electricity that is 150% higher than the baseline project or 19.9¢/kWh compared to 8.0 ¢/kWh. Even a doubling of that efficiency up to 40% will produce a COE of 10¢/kWh.

Sensitivity Analysis to Competitive COE Levels

The final sensitivity to be examined is the level of subsidy required to reduce the TPI for the baseline tidal power plant to be competitive with current new construction wind energy systems.

This analysis uses a COE cut-off value of 5.0 ¢/kWh. This critical analysis value is based on a weighted combination of factors. A value put forward by the California Energy Commission as the COE for newly constructed wind farms (value inflation adjusted from its reported 2002 value). The improved cost structure of wind farms that has resulted from greatly expanded experience and better best practice knowledge, as well as significant technological improvements in construction and manufacturing practices. Table 6.4 below reports the COE that would result from a reduced TPI that would need to be recovered during the project's lifetime.

The reduced TPI is assumed to be the result of major project development and construction subsidies.

Hypothetical Scenario

The baseline project is constructed and commissioned as designed. The expected TPI will be $145.6 million and AO&M costs will be $7.8 million for the life of the project.

To make the project competitive with the COE of contemporaneously built commercial-scale wind farms a construction subsidy is given to the developer. All TPI not paid by the subsidy must be recovered in the COE.

The AO&M will remain unchanged, as it is not affected by any construction costs subsidy.

Table 6.5 shows that the maximum TPI that can be incurred for repayment by the project is $36.25 million.

Table 6.5 Cost of Electricity (¢/kWh) – Equivalent COE to New Wind Systems

Total Project Investment ($million)	**36.25m**
Levelized Annual O&M	
7.8m	**5.00 (4.46)**
Nominal $2007 *(Constant value)*	

For the tidal power plant to be competitive with a newly constructed wind farm on a COE basis the TPI would have to decrease by $109.3 million. This is the level of subsidy required. This represents a 75% reduction in Total Plant Investment.

Economic Feasibility of a Tidal Energy Project base on COE

The section provides discussion on various considerations that help set the stage for current investigations into the feasibility of tidal energy production.

Why Tidal Energy Now?

Traditional market forces within the electric power industry have excluded the deployment of most all non-fossil fuelled generating power plants up to this time. The only significant sources of electric power that are non-fossil fuelled are hydroelectric generation schemes and nuclear powered generation plants.

Alternative generation sources have not been developed and deployed on a commercial-scale because the cost of energy from such facilities would not have been competitive with established technologies that are fueled by coal and natural gas, nuclear power, and hydro. Competition based on cost of production has become even more difficult for alternative technologies during the past decades as natural gas fuelled generating facilities have seen large improvements in cost efficiency from the deployment of combined-cycle technology which have relatively low capital investment costs, higher load factors, and a substantial increase in combustion efficiency ratings compared to standard combustion natural gas plants. The next generation of nuclear-fuelled power plants has shown potential for lower costs and decreased financial and environmental risks, and will likely present some threat in coming decades.

However, there are new external economic, political, and environmental issues that have now impinged into any decision about which type of generating technology should be added to an electric power company's portfolio. The economic feasibility of alternative energy sources, specific to this discussion - tidal energy conversion technology, have now become viable in the near term as a result.

The single most important reason why tidal power technology may become an economically viable technology for Tacoma Power is the recent creation of a renewable portfolio standard in the State of Washington. This is a legal requirement put on Tacoma Power and other qualifying electric utility companies within the state to match a proportion of their total volume of electricity sales, measured in MWh, with renewable energy credits. The renewable energy credits can only come from eligible electricity producers who use approved alternative technologies within the Pacific Northwest. Tacoma Power is obligated to either purchase the RECs from eligible producers or create them internally. If Tacoma Power chooses to purchase the required amount of RECs, they must either go to the open market to either negotiate bilateral contracts for the RECs or purchase them from the spot markets that are being operated by REC brokers. The other option is to create RECs internally. In which case Tacoma Power must expand or in some way modify their portfolio of generating assets to include an approved generating facility or facilities.

Risks in the REC Market

The government created market system using RECs and an RPS acts to create monetary value for a secondary attribute of electricity production; namely, the production of electricity without the co-production of air-borne carbon pollution. The REC/RPS market structure allows the negative environmental effects of carbon pollution to be monetarised and therefore it can be included in the financial costs and benefits in determining optimal generating assets.

The market exchange price at which RECs will be bought and sold will be subject to normal supply and demand constraints. The annual demand for RECs will be fairly transparent for all relevant parties to see. The annual electric energy production, which is delivered by retail distribution companies, is generally forecasted with a good degree of accuracy. The major source of unpredictable energy demand, increase or decrease, will come from seasonally weather patterns.

The supply side of RECs is perfectly correlated with the delivery of energy from renewable energy power project. Typically, across America one REC is issued for one MWh of electricity delivered for commercial use through the grid. While this is not uniform across the country, it is a sufficient generality. This half of the market is much more volatile than the demand side. The supply will be highly dependent on seasonally weather patterns, with calm dry weather leading to lower production of energy and RECs from renewable energy projects with rely hydro and wind resources. The other major source of volatility is the rate and manner in which new renewable energy projects will be developed and deployed. Supply will grow in smooth continuous fashion but in a step-wise manner with projects coming online in large chunks as commercial-scale projects are commissioned. The rate of development and deployment of commercial projects will be dependent on local and regional planning, grid infrastructure to transport the energy, and the level of risk and reward which developers are willing to accept.

Given the statutory requirement for qualifying utilities to participate in the REC/RPS program the price could theoretically be bid up to multiple times the value of the actually electricity being delivered. It is common that a penalty fee or a buy-out option be offered to participating companies that will allow them to pay cash to meet their obligation rather than participate in the REC market. This allows greater flexibility to the firm in determining the optimal financially responsible behavior and decision-making. Firms can choose the least expensive option between participating in the market and delivering RECs to meet their obligation or simply pay the equivalent in cash.

Accurate long range forecasting of REC prices is difficult because of this volatility in supply. Long range being defined as greater than 5 years and is principally determined by the timeframe to plan, permit and construct eligible renewable energy projects.

The market price of RECs have the potential to be as high as the buy-out penalty to as low as zero. There is a theoretical potential for RECs prices to have no value if there is more supply than there is demand. Although this scenario is an unlikely event, as creation of REC will be dampened as new project are terminated prior to commissioning and exiting renewable energy producers will shutdown operations if the revenue stream from selling RECs and electricity is insufficient to cover their average cost of operations.

Another factor that determines the economic feasibility of alternative energy production is if the obligated electricity supplier internalizes the operation of an eligible renewable energy system. If a renewable energy system is owned and operated by a utility, 100% of the value of the RECs maybe captured as the avoided the cost of paying either the REC market price or the buy-out penalty. The purchase of RECs from an outside vendor, whether it be through a broker or directly from a private power producer, will include the appropriate markup from production costs to for-profit sales price. This may be quite small or large, depending on the producers' particular profile, i.e., discount rate, efficiency and expertise, etc.

Other Factors

The economic feasibility of renewable energy projects is also determined by a different project cost structure than traditional power plants. Several types of cost elements must be taken into account: capital costs of the generating plant, associated infrastructure costs, operation and maintenance, fuel and decommissioning.

For most renewable energy systems, the capital costs of construction and commissioning are the largest expense category and the dominant component in any COE calculation. The capital cost per MW of capacity of a hydro power plant is likely to be 500% larger than the capital cost of a natural gas combined cycle power plant. Cost differences for tidal energy projects are expected to be of the same magnitude.

Associated infrastructure costs are proving to be a major component that is not included a COE analysis. Commercial-scale renewable energy systems by their very nature tend to be located in areas that are distant from load centers, so connection at the grid level is required. The construction of a new transmission line for transport of the electricity may be a very significant cost. In addition, unless the transmission line has sufficient spare capacity the line will likely have scheduling difficulties. With the exception of stored hydroelectric schemes, most renewable energy projects are intermittent in production and are non-dispatchable. To assure transmission of the energy when it is being produced the transmission line will have to maintain excess capacity or be able to reject dispatchable production when renewable energy is available.

Areas for Future Research

Experience/Learning Curve Analysis – there is substantial uncertainty about the timeframe in which tidal flow energy systems will be deployable at a commercial scale. Analysis of actual improvements in technological cost efficiency over previous iterations of tidal energy system technology will give a more accurate prediction on deployment. This can act to moderate the voices of technologic optimism and detractors.

Economic Efficiency Analysis of Complete Tidal Energy Systems – identification of those components that act as constraints on overall cost efficiency. This research would assist in determining the components that could deliver the best gains from research/engineering resources.

Geographic Economic Feasible Map – development of a resource map based on economic costs factors, i.e., access to transmission, environmental issues, competing resource use, etc., which indicates tidal energy resource areas with the greatest potential for development.

Social Value of Tidal Energy Systems – tidal energy systems may have significantly different social preferences than other renewable energy sources like wind, hydro or solar, as well as traditional fossil-fuelled combustion power plants. Such factors are likely to influence the allocation of government subsidies and research funds to develop tidal energy if a greater social preference can be shown.

Conclusions

Tacoma Power is investigating the potential development of a tidal power plant to be deployed in the Tacoma Narrows. The municipal utility currently has excess generating capacity and as a regular occurrence sells electricity to other utilities in Washington State and potentially to other users in the Western United States and Canada. There appears to be no need in the near term for additional generating assets to be added to Tacoma Power's portfolio.

Tacoma Power's primary interest in a tidal power plant is as a means of producing renewable energy credits to meet the impending mandates created by I-937. By internalizing the production of RECs, there exists potential to reduce the risk of market volatility and price uncertainty when relying on the REC market.

The Washington State mandate limits the geographic region from which REC maybe produced for use in meeting the portfolio standard. This adds to the potential volatility of the market. The annual market demand for RECs will be known within a small confidence interval but the annual production of RECs will have a much greater level of uncertainty. REC production is now and will be into the future highly dependent on regional weather patterns and cycles, specifically renewable energy systems like hydro and wind are impacted. The fluctuation in REC supply will be a source of price uncertainty from year-to-year.

Note, however, that the additional cost of purchasing RECs would only be incurred on the 3% of its load it is required to match with RECs under I-937 to start with.

The maximum penalty that may be incurred as a result of non-compliance with I-937 is $50.00 per MWh. This translates to 5¢/kWh. Again, this would only apply to that portion of the mandate that was not covered by RECs submitted by Tacoma Power.

It is clear that the tidal power plant under consideration is not economically feasible at this time. With a baseline best-case scenario of 8.0¢/kWh and a best case scenario of 7.0¢/kWh if a 20% reduction in TPI could be attained on the best-case scenario.

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COE Model for Tacoma Power Tidal Energy Project

Tacoma Power COE model is attached as an independent file.